CHAPTER 13

Florida's Oceans and Marine Habitats in a Changing Climate

Steven Morey[1], Marguerite Koch[2], Yanyun Liu[3], and Sang-Ki Lee[4]

[1]Center for Ocean-Atmospheric Prediction Studies, Florida State University, Tallahassee, FL; [2]Department of Biological Sciences, Florida Atlantic University, Boca Raton, FL; [3]Cooperative Institute for Marine and Atmospheric Studies, University of Miami, Miami, FL; [4]Atlantic Oceanographic and Meteorological Laboratory, National Oceanic and Atmospheric Administration, Miami, FL

Florida's peninsula extending ~700 km north-to-south, extensive shoreline (2,100 km), and broad carbonate platform create a diversity of marine habitats (estuaries, lagoons, bays, beach, reef, shelf, pelagic) along the coast, shelf, and deep ocean that are influenced by continental, oceanographic, and atmospheric processes all predicted to shift with a rapidly changing climate. Future changes of the global ocean circulation could result in a 25% reduction in the Atlantic Meridional Overturning Circulation (AMOC), leading to a subsequent slowing of Florida's regional/local current systems (Yucatan, Loop, Florida and Gulf Stream) and eddies. While downscaled climate models suggest that slowing of the Loop Current by 20-25% during the 21st century will moderate the increase in surface temperatures in the Gulf of Mexico to 1.4°C - 2.8°C, this warming is predicted to have wide-ranging consequences for Florida's marine habitats (e.g., enhanced coral bleaching, lower O_2 in surface waters, increased harmful algal blooms, reduced phytoplankton and fisheries production, and lower sea turtle reproduction). The reduction in the AMOC is also predicted to reduce hurricane frequency, albeit with increased intensity (2-11%) due to ocean warming. Climate projections affecting Florida's oceans include rises in sea level, changes in coastal circulation impacting larval and nutrient transport, changes in marine biogeochemistry including ocean acidification, and loss of coastal wetlands that protect Florida's coastline. Understanding the consequences of these projected climate impacts and gaining a more complete understanding of complex changes in atmospheric processes (e.g., ENSO, AMO, convection, wind shear), air-sea interaction, currents, and stratification under a changing climate is critical over the next few decades to prepare and protect the state of Florida.

Key Messages

- Florida has a unique peninsular geography that creates an extensive shoreline with a diversity of marine habitats along the coast, shelf, and deep ocean influenced by continental, oceanographic, and atmospheric processes all predicted to shift with a rapidly changing climate.
- Climate projections affecting Florida's oceans include rise in sea level, warmer sea surface temperatures, changes in coastal circulation impacting larval and nutrient transport, changes in marine biogeochemistry including ocean acidification, and loss of coastal wetlands and reefs that protect Florida's coastline.
- Downscaled ocean models have proven successful for understanding future changes for the region given climate projections, and their continued revision and improvement will result in a more complete understanding of complex changes in air-sea interaction, large-scale currents, and the rates of climate change impacts, a critical research need over the next few decades to prepare and protect the state of Florida.

Keywords

Ocean climate; Sea level rise; Florida climate; Gulf of Mexico; AMOC; Caribbean climate; Florida hydrology; Florida reefs; Global warming

Introduction

Geomorphology

Florida's unique peninsular shape, with over 2,100 km (1,304 mi) of shoreline extending approximately 700 km (435 mi) north-to-south and a broad subsurface carbonate platform, creates a diversity of marine environments along the coast, shelf, and deep basins that are subject to influence by regional and global climate and ocean circulation patterns (Fig. 13.1). The geomorphology of the shelf that encircles Florida influences coastal connectivity to deep basins in the Gulf of Mexico and Atlantic Ocean (Fig. 13.1). For example, a narrow shelf at the head of the De Soto Canyon along the western extent of the state connects shelf and coastal waters with deep oceanic basins within the Gulf of Mexico (Fig. 13.1). The West Florida Shelf (WFS) – a long, broad, flat carbonate platform – buffers the west coast of the peninsula from the offshore waters of the Gulf. At the southern tip of the peninsula, the Florida Keys are proximate to the shelf edge with the shallow Florida Bay to the north and the deeper Straits of Florida to the south (Fig. 13.1). Along Florida's East Coast, the shelf is a narrow strip at the southern part of the peninsula that widens northward as part of the South Atlantic Bight, which extends offshore of North Carolina.

Coastal Hydrography

Coastal regions are buffered from the open ocean by wide continental shelves along much of Florida's coastline. The hydrography (physical properties of seawater) of these coastal waters is more heavily influenced by local atmospheric forcing and rivers than by the deep ocean, an example of how geomorphology is linked to hydrography. The northern parts of Florida, including the Panhandle, Big Bend, and northeastern regions, experience distinct seasonal climate regimes during the year, with a strong continental influence in the cool months and coastal humid subtropical conditions during the warm months. Numerous rivers along the coast discharge fresh water that mixes with ocean waters before being exported to deeper water. Many of Florida's rivers, which discharge into estuaries and coastal lagoons, have relatively local watersheds. Notable exceptions include rivers in the Apalachicola Basin, which encompasses the Chattahoochee and Flint rivers in eastern Alabama and western Georgia. These coastal, shallow water systems are adjacent to larger regional and global current systems that have significant influences on Florida's climate, coastal hazards (storm surges), seawater temperature regimes, and productivity of marine habitats.

Current Systems

The major regional and global ocean currents that are proximate to the Florida Peninsula are illustrated in Fig. 13.1. Along the eastern coastline of Florida, the subtropical North Atlantic Ocean has an intensified western boundary current linked to the Florida and Antilles currents, generally referred to as the Gulf Stream system, which flows northward (Fig. 13.1). The Gulf Stream system is a component of the global thermohaline circulation or Atlantic Meridional Overturning Circulation (AMOC; Fig. 13.1). The proximity of the Gulf Stream system to Florida provides a strong connection between Florida's marine environments and the global ocean circulation. A branch of this western Atlantic boundary current that enters the Gulf of Mexico from the Caribbean Sea through the Yucatan Channel forms the Loop Current, which turns eastward and exits the Gulf through the Straits of Florida. This current then flows northward along the east Florida coast as the Florida Current (Fig. 13.1).

The Florida Current/Gulf Stream system is globally significant as it is responsible for poleward transport of approximately 32 Sv (Sverdrups) of seawater (Barringer and Larsen 2001), equating to 32 million cubic meters of water per second (10^6 m^3 s^{-1}) and 1.3 PW (Petawatts), or 1.3 quadrillion watts (10^{15} W) of thermal energy (Larsen 1992). Thus, Florida currents are an integral part of the global current system (AMOC) and contribute to the planetary energy balance between the tropics and poles. Because these global currents are so inextricably linked to Florida's regional currents, the state and its coastline experience climate and hydrological reverberations as these global currents change in response to large-scale global shifts in flow (Ezer 2015). This local-global current interaction and the low elevation of Florida make the state vulnerable to even modest changes in global ocean circulation patterns.

Natural Variability of Florida's Oceans

Florida's marine areas experience large natural variability at seasonal, interannual, and longer time scales, largely due to atmospheric forcing. Certain climate modes (repeatable, naturally occurring patterns in the dynamic climate system) have very pronounced impacts on Florida's oceans. Shallow nearshore regions generally exhibit greater variability as a response to the overlying atmosphere than do the deeper offshore regions, which are influenced both by local atmospheric forcing and remote atmospheric forcing acting on large-scale ocean circulation patterns. It is important to understand the variability of oceanic properties that responds to natural fluctuations in climate or seasonal forcing in order to evaluate projections of influences of future climate change on Florida's oceans in the proper context.

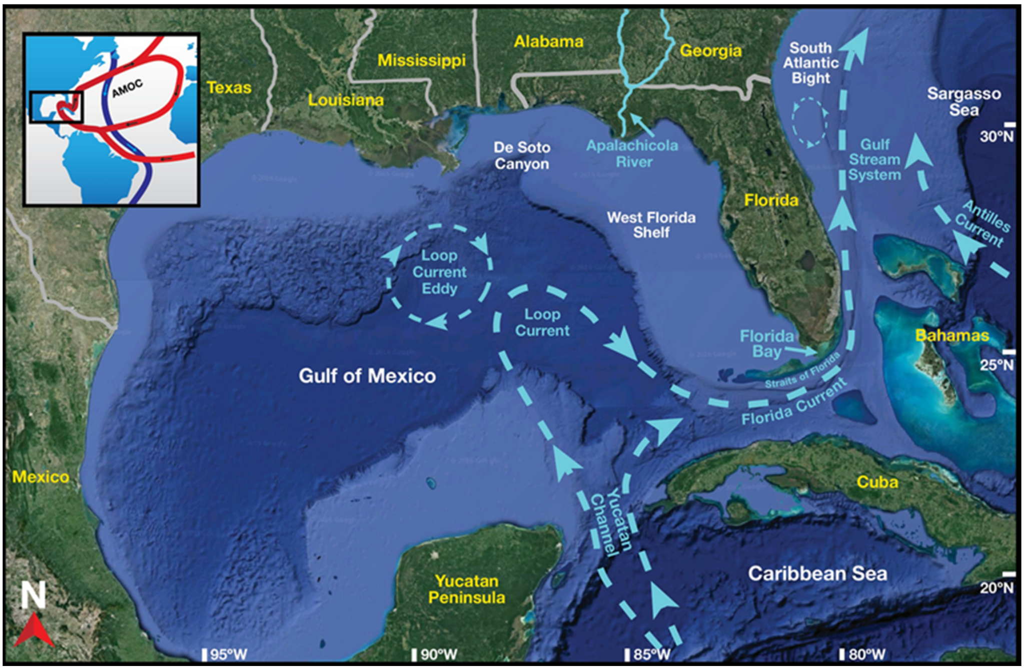

Figure 13.1. Map depicting the peninsular state of Florida. The West Florida Shelf (WFS), eastern shelf, as the southern extent of the South Atlantic Bight, De Soto Canyon, Gulf of Mexico, and western subtropical Atlantic Ocean (Sargasso Sea) are shown with a schematic representation of large-scale currents influencing waters around the state. The variable Loop Current is represented in its retracted and extended states emerging from the Yucatan Channel. A single representation of a Loop Current eddy is shown, though these generally westward migrating features (cyclonic and anticyclonic) are nearly ubiquitous throughout the deep western Gulf. The insert in upper left corner illustrates the connectivity of Florida's local and regional currents (Loop/Florida/Gulf Stream System) with the Atlantic Meridional Overturning Circulation (AMOC); arrows indicate dominant flow of red warm surface currents and blue arrows cold subsurface currents within the AMOC. *Illustration credit: Chris Johnson. Image credit: Google Maps.*

Seasonal Climatology

Currents

The deep water currents offshore of Florida's coasts are generally either persistent (such as the Florida Current) or have large-amplitude variability due to their stochastic (random, but behaving in a statistically meaningful fashion) nature (for instance, the Loop Current). However, there is evidence of some seasonality in the Florida Current. Variations in its transport are roughly ±10% of the mean, and the annual cycle is strongly affected by longer climate modes, such as the North Atlantic Oscillation (NAO) (Baringer and Larsen 2001; Peng et al. 2009).

Over the shallow shelf regions, currents vary more strongly due to direct atmospheric forcing. Low frequency variations in the coastal and shelf currents are along isobaths (lines of constant depth) and are a response to the along-shelf component of local wind stress. Over the Florida Gulf coastal waters, winter cold front passages are characterized by rotation of local winds from the southeast to the northwest at typically three- to ten-day intervals. These winds force alternating flow direction along much of the northern WFS and Panhandle region, with asymmetry in the strength of the northwesterly winds driving eastward and southeastward seasonal flow (Todd et al., 2014). The local wind climatology shows that dominantly northerly wintertime winds shift to easterly and southerly through the spring and summer, weakening during the summer months before strengthening and rotating back easterly and northeasterly during the fall (Zavala-Hidalgo et al., 2014). The effect of the seasonal shift between light southerly winds and stronger northeasterly winds is evident in the trajectories of surface drifters that measure currents over the WFS and Panhandle coastal waters, with movement strongly westward during the fall-winter and eastward during the summer (Morey et al., 2003).

A similar seasonal shift in the wind regime also affects currents inshore of the Florida Current along the eastern (particularly northeastern) coast of Florida. Northerly winds during the winter prevail, forcing a southward flowing coastal counter current. However, as winds shift to a more southerly direction, this countercurrent ceases. The southerly winds create upwelling along the narrow shelf off Florida's East Coast. This upwelling forces cool and more nutrient-rich water from depth onto the shelf in the spring and summer.

Changes in seawater density structure can also induce seasonally varying buoyancy-driven currents, particularly near river plumes. Thermal gradients due to differential cooling over the sloping shelf can also induce buoyancy-driven currents. For example, a springtime mid-shelf cold tongue along the northern WFS impacts circulation over the shelf at seasonal time scales (He and Weisberg 2002).

Temperature

Coastal ocean temperature is strongly affected by the distinct warm and cool seasons through surface heat fluxes. Net surface heat flux is the sum of the shortwave and longwave radiative energy that is absorbed or emitted by the ocean, and sensible (conduction) and latent (evaporative) heat fluxes. The radiative fluxes are largely dependent upon the season (amount of incoming solar radiation at the top of the atmosphere), cloudiness, ocean temperature, and ocean turbidity. The sensible and latent heat fluxes depend on the atmospheric state and ocean surface temperature. During much of the year net heat flux acts to warm the ocean around Florida. As the amount of incoming solar radiation decreases going into the winter season, and cool dry air masses with strong winds associated with cold fronts pass over the ocean, surface waters cool. This cooling is stronger in North Florida than in South Florida due to the change in solar radiation, frequency and strength of the cold fronts (Fig. 13.2). However, southern seasonal cooling can occur when cold fronts occasionally reach as far south as the Florida Keys, as well as when the Loop Current stretches far into the northern Gulf and this cooled water is subsequently advected south into the Florida Straits (Rudzin et al, 2013).

The transition between cooling and warming regimes over coastal waters (largely isolated from strong temperature advection by offshore currents) occurs when the net surface heat flux shifts between negative and positive (using the convention of positive heat fluxes being directed into the ocean). The timing of these seasonal transitions varies from year to year and with latitude, but climatologically the spring transition occurs around late February to early March and the fall transition occurs during September in Florida waters.

Salinity

Another important factor influencing variability of hydrographic conditions in Florida's coastal waters is the variation of discharge from rivers, particularly those with large watersheds such as the Apalachicola River. This river exhibits strong seasonal variability (Fig. 13.3), with important changes at interannual and longer time scales, mimicking the hydrological conditions over the watershed with a lag of several weeks (Morey et al., 2009). The spring maximum discharge by this and other regional rivers not only affects the coastal salinity, but also ocean optical properties, including those associated with phytoplankton pigments, over a broad region of the northern WFS extending out to 200 km from the coast through input of nutrients and organic matter. In contrast, Florida's East Coast has little freshwater input by rivers compared to the Gulf Coast, but these may substantially impact coastal water quality due primarily to dense human development and agricultural activities along their watersheds.

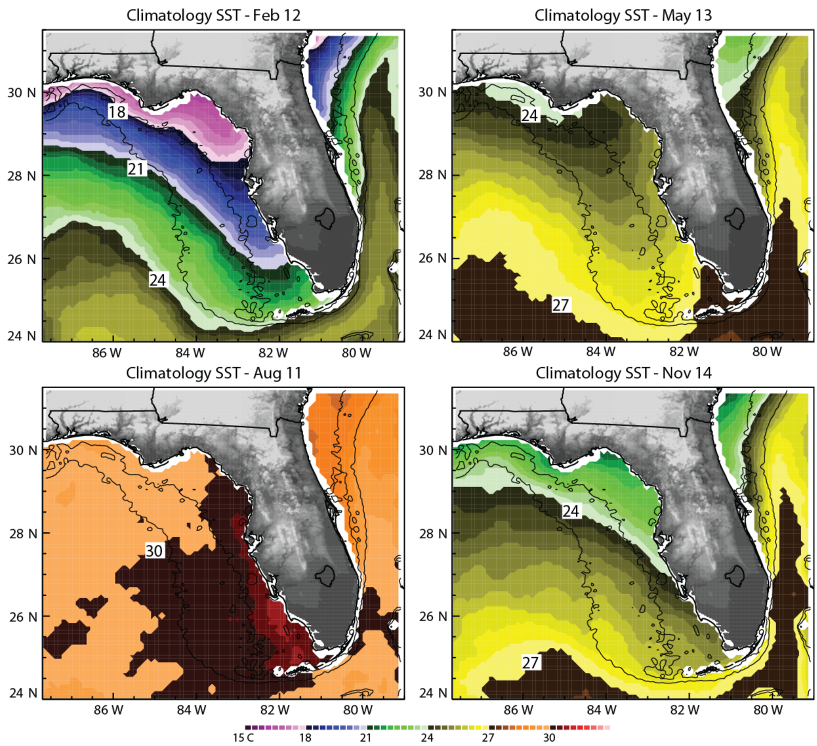

Figure 13.2. Sea surface temperature (SST) climatology maps from the NASA/JPL AVHRR 9 km 5-Day Climatology (1985-1999) (Casey and Cornillon, 1999) shown near the peaks of the cold and warm seasons (February 12 and August 11) and from spring and fall transition periods (May 13 and November 14).

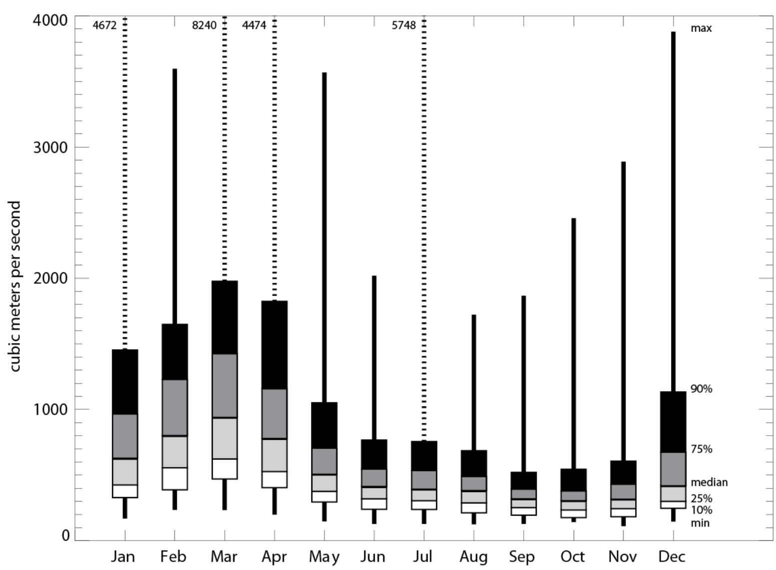

Figure 13.3. Distributions of the Apalachicola River daily flow rates (measured at Chattahoochee, Florida from 1929 through 2007) by month. The 10th, 25th, 50th (median), 75th, and 90th percentiles are shown with the recorded maximum and minimum. Dotted maxima lines extend beyond the plotting limits and the true maxima values are indicated. From Morey et al. (2009).

Interannual and Interdecadal Ocean Climate Variability

Interannual variability in the region is strongly linked with the El Niño/Southern Oscillation (ENSO). Though ENSO is an equatorial Pacific phenomenon, atmospheric teleconnections cause impacts across the southeastern United States, Gulf of Mexico and subtropical Atlantic. In particular, a significant precipitation signal over the southeastern US is connected to ENSO, with higher rainfall during the warm (El Niño) phase (Ropelewski and Halpert 1986) and reduced precipitation over the region during the cold (La Niña) phase (Smith et al. 1998). This leads to interannual variability in the coastal ocean salinity and optical properties through changes in river discharge rates (Morey et al. 2009). These ENSO impacts on precipitation and discharge of Florida's rivers are primarily observed in the late winter (Schmidt et al. 2001).

ENSO also modulates the occurrence of hurricane landfalls in the US, with fewer strikes during the El Niño phase (Bove et al. 1998), but the long-term variability of the impacts of such episodic events on Florida's oceans is difficult to ascertain given their relative infrequency. However, ENSO also modulates the occurrence and tracks of extratropical cyclones in the Gulf of Mexico (Eichler and Higgins 2006), which in turn impacts the likelihood of extreme coastal sea level fluctuations associated with these storms with greater extrema during the El Niño phase along the Gulf Coast (Kennedy et al. 2007).

Though the direct observational record remains too short to clearly show strong links between variability in the Gulf of Mexico and interdecadal climate modes such as the Atlantic Multidecadal Oscillation (AMO, with period of roughly 70 years), there is compelling evidence to suggest that the longer modes of variability can have important consequences on Florida's coastal waters. These impacts may include modulation of interannual climate signals. For example, Enfield et al. (2001) examined the interdecadal modulation of the ENSO teleconnections, suggesting a greater correlation between rainfall over the southeastern United States and the Southern Oscillation during the cold phase of the AMO. Using proxy records from tree ring analysis and chemical analysis of sediment box cores, Poore et al (2009) showed that multidecadal-scale variability occurs in the northern Gulf of Mexico sea surface temperature (SST) and may be linked with the AMO.

Atmospheric Forcing in a Future Climate

As discussed in the previous sections, atmospheric variability is a strong driver of variability in ocean currents and hydrographic properties around Florida, particularly in shallow shelf and coastal waters. Thus, in order to understand how Florida's waters may change under a future climate, it is necessary to understand the potential atmospheric changes over various spatial and temporal scales that are likely to occur. The Intergovernmental Panel for Climate Change's Fifth Assessment Report (IPCC-AR5 2013) showed that the most pronounced atmospheric changes in the ocean regions surrounding Florida during the 21st century are expected to occur in the boreal summer season (IPCC, 2013). They include the reductions of summer rainfall in the Caribbean Sea (Rauscher et al. 2008; 2011), a reduction in Atlantic hurricane activity (Vecchi and Soden 2007), and the intensification of the North Atlantic subtropical high pressure system (Li et al. 2012). The following sections briefly review recent works on these projected changes and the associated physical mechanisms.

Warming and Drying of the Caribbean Sea

Under the different IPCC-AR5 climate projections based on different atmospheric greenhouse gas concentration scenarios, the global ocean is generally expected to warm. However, there are substantial regional differences in warming rates. This regional variability in warming has important consequences for Florida's future oceanic climate. The Caribbean Sea is projected to warm less than other tropical (specifically, Indo-Pacific) waters. Cooler North Atlantic SSTs are associated with a decrease in the AMOC, which transports warm water northward (e.g., Delworth and Mann 2000; Knight et al. 2006). IPCC-AR5 projects a significantly weakened (by about 25%) AMOC in the 21st century that could be responsible for suppressed warming of the Caribbean. Another potential contribution to the suppression of warming of the Caribbean Sea is that a uniform increase of global SSTs may result in a greater evaporative cooling response in a region of high mean surface wind speed, such as in the Caribbean Sea (Leloup and Clement 2009; Xie et al. 2010).

According to the second lowest greenhouse gas concentration trajectory adopted by IPCC-AR5 (IPCC 2013), the Representative Concentration Pathway (RCP) 4.5 scenario, the Caribbean Sea is likely to experience a reduction in rainfall of ~10% in the boreal summer by 2100. As shown in Rauscher et al. (2008), the projected drying in the Caribbean Sea can be described as an extension and intensification of the Meso-American mid-summer drought (e.g., Mapes et al. 2005). Lee et al. (2011) and Rauscher et al. (2011) demonstrated that the reduced warming of the tropical North Atlantic compared to surrounding ocean decreases convection, promoting lower relative humidity and reduced precipitation in the Caribbean Sea. These changes have implications for hurricanes impacting Florida's oceans and coastal regions, as well as basin-scale circulation patterns affecting Florida's offshore regions.

Projected Reduction of Atlantic Hurricane Activity

Hurricanes, though episodic events, have profound impacts on Florida's oceans and coastal regions and thus serve as a major link between Caribbean climate and Florida's climate. The reduced convection over the Caribbean Sea is anticipated to result in an increase in wind shear that would reduce the frequency of hurricanes in the region (Lee et al. 2011). According to the IPCC Fourth Assessment Report (IPCC-AR4), global climate model simulations under various scenarios predict an overall increase in the vertical wind shear in the Main Development Region (MDR) for Atlantic hurricanes (10°–20°N, 85°–15°W), with relatively large multi-decadal variation in the 20th and 21st centuries. This occurs along with significantly reduced convection in the MDR from 1900 to 2100 (Lee et al. 2011), another condition not favorable for hurricanes.

Future projections based on theory and high-resolution dynamical models consistently indicate that, due to the increased vertical wind shear and decreased convective instability in the MDR, Atlantic cyclone activity could be significantly reduced in the 21st century despite a large increase in the SSTs (Vecchi and Soden 2007). However, existing dynamic models also project that greenhouse warming could cause the globally averaged intensity of tropical cyclones to shift towards stronger storms, with intensity increases of 2–11% by 2100. (Knutson et al. 2010).

Intensification of the North Atlantic Subtropical High Pressure System

Li et al. (2012) projected that drying in the Caribbean Sea in the 21st century increases the regional sea level pressure, and is thus linked to the westward expansion and intensification of the North Atlantic subtropical high pressure system. This high pressure system not only is a major driver of Florida's climate, but also forces the large-scale anticyclonic subtropical gyre circulation in the North Atlantic.

Intensification of the North Atlantic subtropical high under future climate scenarios will lead to enhanced easterly trade winds in the tropics and mid-latitude westerlies in the North Atlantic. This strengthening of the trades and westerlies is expected to force a stronger circulation of the North Atlantic subtropical gyre that is the major oceanic circulation feature of the Atlantic located east of Florida.

Temperature and Salinity Changes in Florida's Oceans in a Future Climate

Due to increasing greenhouse gas emissions, climate model simulations project a greater than 2°C increase in upper ocean temperatures in the Gulf of Mexico by the end of this century (Coupled Model Inter-comparison Project phase-3 – CMIP3 – and phase-5 – CMIP5; Liu et al. 2012, 2015). Further, a 20-25% slowing of the AMOC is also predicted by 2100 (Liu et al. 2012, 2015; Cheng et al. 2013). These changes could substantially affect the hydrographic and biogeochemical properties of the seawater, with important consequences for marine ecosystems in the state. However, the global climate models (CMIP3/CMIP5) have a typical spatial resolution (grid spacing) of about 1° of latitude/longitude, which is too coarse to properly resolve the strength, position, and eddy shedding characteristics of the Western Boundary Current systems such as the Caribbean Current, Yucatan Current, and Loop Current (Oey et al. 2005). Thus, the global climate models cannot be used by themselves to address future changes in these currents.

Liu et al. (2012) addressed the issues of using coarse-resolution global models for studies of the region by using higher resolution (0.1° grid spacing) models nested within the global climate models (CMIP3) to dynamically downscale the global model projections for the Gulf of Mexico region. The downscaled simulations predict that the Loop Current transport will be reduced by up to 20-25% during the 21st century. These simulations further show that the projected Loop Current reduction and associated weakening of warm Loop Current eddies could suppress the surface warming in the Gulf of Mexico, particularly in the northern deep basin. These results are in contrast to the low-resolution global climate models, which underestimate the projected reduction of the Loop Current and predict greater warming in the Gulf, partly due to the inability of these models to accurately simulate oceanic eddies. These results clearly show the utility of using high-resolution models to downscale global climate projections to a regional level.

SST Changes in the Gulf of Mexico during the 21st Century

A similar downscaling approach using the CMIP5 as forcing for historical and two future climate change scenarios (RCP4.5 for medium-low emission scenario and RCP8.5 for high emission scenario, Taylor et al. 2012) was used to further understand the warming and natural climate variability in the Gulf of Mexico (Liu et al. 2015). This model reproduced basin-averaged SST variability in the Gulf of Mexico during the 20th century reasonably well compared to analysis of historic observations (Fig. 13.4a), which supports the use of the downscaled modeling approach for climate studies. Under the RCP8.5 scenario, the downscaled model projects the annual average SSTs in the Gulf of Mexico to increase from 26°C in the late 20th century to slightly above 29°C by 2100 (Fig. 13.4b). It is important to note the uncertainty of future projections due to natural climate variability, given by the standard deviation (STD) of SST anomalies within the Gulf (STD = 0.21° C, Fig. 13.4b). Under RCP4.5 (RCP8.5), a trend of SST in the Gulf of Mexico shorter than 26 years (13 years) cannot be used to distinguish the greenhouse gas effect from natural variability.

The Gulf of Mexico warms by 1.2 ~ 2ºC (3ºC or more) under RCP4.5 (RCP8.5) by 2100, based on global low resolution CMIP5 models. In the downscaled simulations (Liu et al. 2015), the Gulf of Mexico also shows extensive warming (Fig. 13.5), but with significant differences in the spatial pattern of the warming, especially during the boreal spring months of April, May, and June (AMJ). During AMJ, the downscaled model-simulated SST increase under RCP4.5 (RCP8.5) in the northern deep Gulf of Mexico is only about 1.4°C (2.8°C), much less than the low resolution model SST increase of 1.8°C (3.4°C). In fact, the northern deep Gulf of Mexico is characterized as the region of minimum warming, whereas it is the region of maximum warming in the low-resolution model projections. The SST increases in the western Gulf of Mexico and the Straits of Florida region are also greatly reduced in the downscaled model compared to the low-resolution global model.

A potential cause for this difference resulting from model resolution may be the weakening of the Loop Current and the associated reduction in the warm water transport through the Yucatan Channel in future scenarios, which are not well simulated in low-resolution global models (e.g., Lee et al. 2007; Liu et al. 2012, 2015). The effect of the Loop Current in the present climate is to warm the Gulf of Mexico. Therefore, a reduction in the Loop Current and the associated weakening of the warm transient Loop Current eddies can result in less warming of the Gulf.

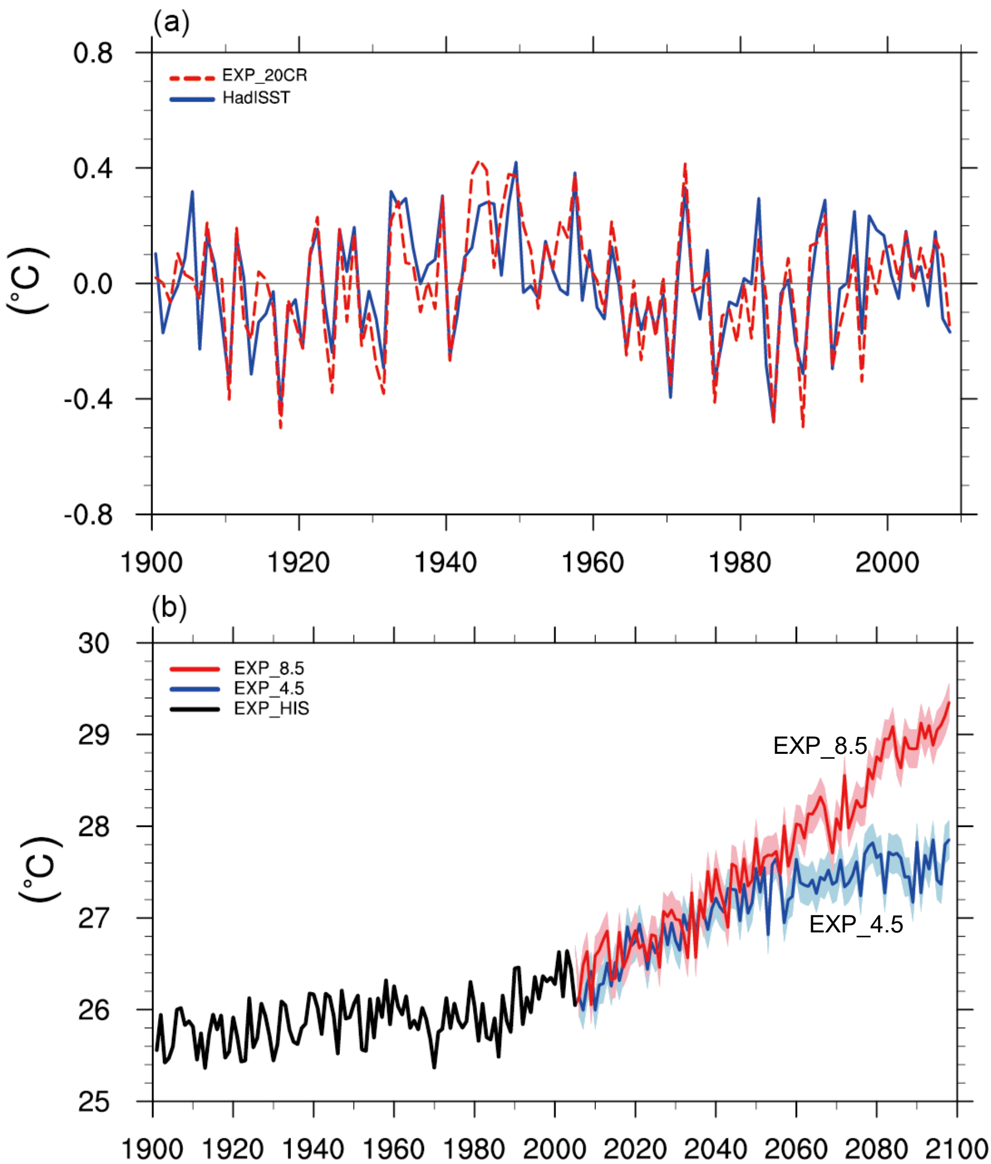

Figure 13.4. (a) Time series of annual mean sea surface temperature (SST) anomalies averaged over the Gulf of Mexico (100°W-82°W, 21°N-30°N) during 1900-2008 obtained from a downscaled model (EXP_20CR, red) and HadISST (blue). (b) Time series of the annual mean SSTs averaged over the Gulf of Mexico during 1900-2098 obtained from downscaled MOM4.1 simulations (20th century simulation [black], RCP4.5 forcing [blue] and RCP8.5 forcing [red]). The standard deviation (STD) of the SST anomalies in the Gulf of Mexico for the period of 1900-2008 is calculated (STD = 0.21°C) and the ± 0.21°C is added to each time point of the future SST projections (light color regions). From Liu et al. (2015).

In contrast to the low-resolution models showing reduced warming in the northern deep Gulf of Mexico, the downscaled model predicts an enhanced warming over the shallow shelf region (< 200 m) of the northeastern Gulf, especially during the boreal summer and early autumn months of August, September, and October (ASO) (Liu et al. 2015). As shown in Figs. 13.5c and 13.5d, the projected SST increase in the northeastern Gulf Coast for ASO is about 4.0°C in the downscaled model under RCP8.5, while the global low-resolution model predicts a SST increase about 3.5°C. In the shallow northeastern Gulf Coast region, the surface ocean circulation is quite weak and dynamically detached from the Loop Current in the deep Gulf of Mexico, and the shelf supresses mixing with cooler deeper waters. Therefore, there is no mechanism to counter the increased surface heating over the shallow northeastern Gulf Coast region. The enhanced summertime warming over the northeastern Gulf Coast could greatly increase the chance for rapid intensification of hurricanes making landfall across the northeastern Gulf Coast in the 21st century and cause greater stratification of surface waters over the shelf.

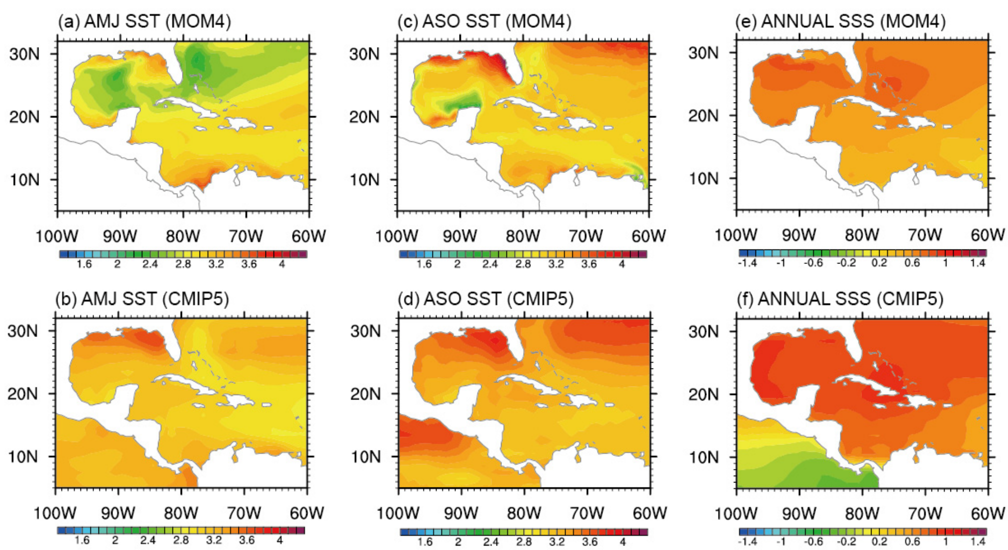

Figure 13.5. Sea surface temperature (SST) differences (°C) in the Gulf of Mexico between the late 21st century (2090 ~ 2098) and late 20th century (1990 ~ 1998) during the boreal spring months of April, May, and June (AMJ) obtained from (a) the downscaled simulation (indicated by "MOM4" in the title) and (b) the weighted ensemble of 18 CMIP5 low- resolution model simulations. Fig (c) and (d) are same as (a) and (b), except for the boreal summer-late autumn months of August, September, and October (ASO). Annual mean sea surface salinity difference in the Gulf of Mexico between the late 21st century and late 20th century obtained from (e) the downscaled model simulation and (f) the weighted ensemble of 18 CMIP5 models simulations. Modified from Liu et al. (2015).

Sea Surface Salinity Changes in the Gulf of Mexico during the 21st Century

As shown in Fig. 13.5e, the sea surface salinity (SSS) is greatly increased almost everywhere in the Gulf of Mexico during the 21st century (up to 1 part-per-thousand [PSU] by 2100 under RCP8.5), consistent with the CMIP5 projected SSS changes as shown in Fig. 13.5f (Terray et al. 2012). This is largely due to the decrease in net surface freshwater flux to the ocean (precipitation minus evaporation) in the Gulf of Mexico during the 21st century. Additionally, in the North Atlantic, the slowing down of AMOC and associated reduced warming of the tropical North Atlantic could also contribute to the projected reduced rainfall in the Gulf of Mexico (Lee et al. 2011).

Projected Reduction of the AMOC and Impact on Gulf of Mexico in the 21st Century

The downscaled climate model simulations project that reductions of the Loop and Caribbean currents in the 21st century play important roles in determining regional warming patterns in the Gulf of Mexico. Therefore, it is important to understand what processes are responsible for the reductions in the strengths of these currents. Fig. 13.6a shows the time series of the simulated annual mean volume transport across the Yucatan Channel for the period 1900-2098 under the historical and two future scenarios (RCP4.5 and RCP8.5). The volume transport across the Yucatan Channel is considerably reduced during the 21st century. The reduction is about 25% of the present mean under RCP8.5. The Caribbean Current is also reduced during the late 21st century (Fig. 13.6b). As shown in Fig. 13.6c, the AMOC at 30°N is reduced during the 21st century under both scenarios. Figs. 13.6d-f further show that the AMOC is highly reduced at all latitudes by the late 21st century (Liu et al. 2012; Cheng et al. 2013). Since the western boundary current system, including the Loop and Caribbean currents, forms an important pathway of the AMOC, it is likely that the reduction in the strength of these currents during the 21st century is driven by the projected deceleration of the AMOC (Liu et al. 2012, 2015).

Consequences of Climate Change for Florida's Marine Habitats

Florida Marine Habitats

Predicted changes in Florida's climate, ocean temperature, tropical storm (frequency and intensity), sea level rise, and current systems will significantly affect marine habitats in Florida (Fig. 13.7), which include: (1) Coastal Estuaries, Bays and Lagoons, (2) Coral Reefs, (3) Beaches, (4) Pelagic Zone, and (5) Shelf Zone. These five broad marine habitats of Florida are described below in the context of the drivers that lead to their function as a habitat, distribution, and ecological services. In the subsequent section, the primary climate change threats to these habitats are discussed.

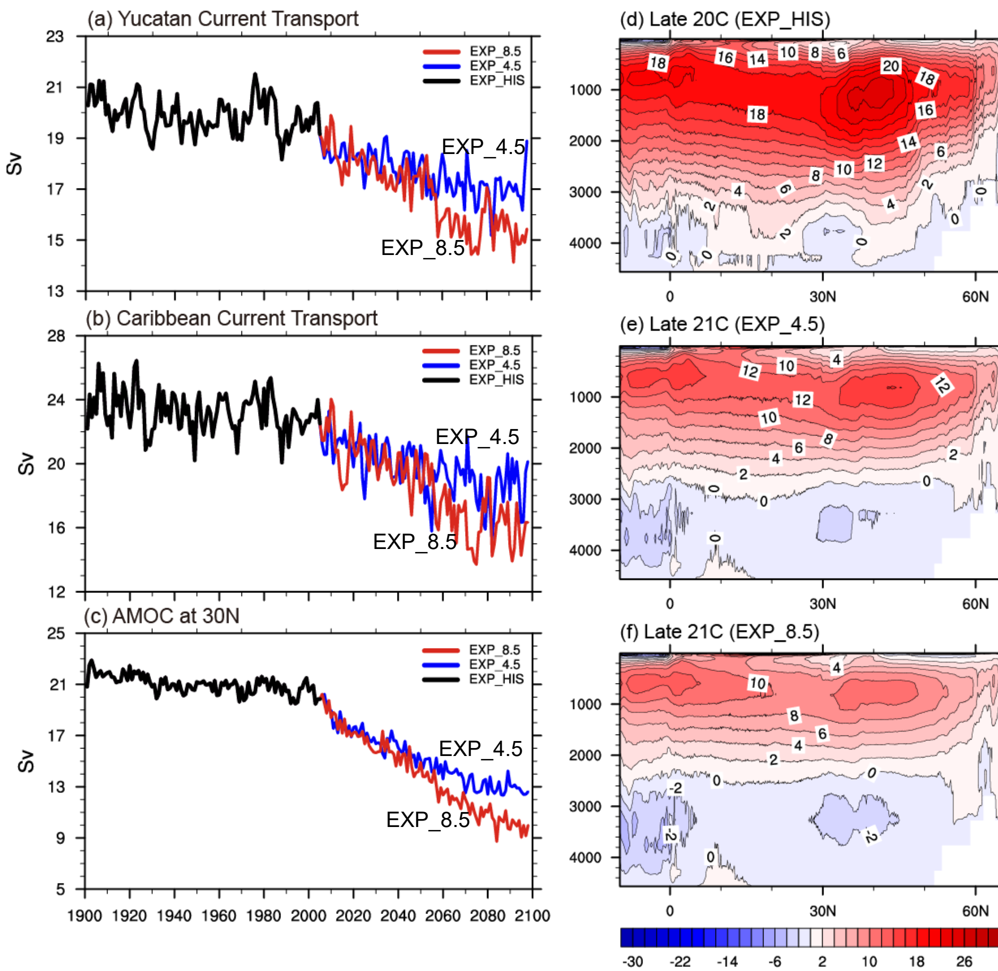

Figure 13.6. Time series of the simulated annual mean volume transport (Sverdrup; 10^6 m^3 s^{-1}) (a) across the Yucatan Channel, (b) in the Caribbean Current, and (c) the Atlantic Meridional Overturning Circulation (AMOC; see Fig. 13.1) at 30ºN for the period 1900-2098 obtained from downscaled model simulations under the historical, RCP4.5 and RCP8.5 scenarios (EXP_HIS, EXP_4.5 and EXP_8.5). Time-averaged AMOC (Sv) in (d) the late 20th century and (e) the late 21st century under RCP4.5 and (f) RCP8.5 scenarios obtained from downscaled model simulations. Depth (1000-4000) is in meters (d-f). From Liu et al (2015). The AMOC plots can be interpreted as depicting circulation along contour lines with higher contour values to the right of the flow when looking at the image.

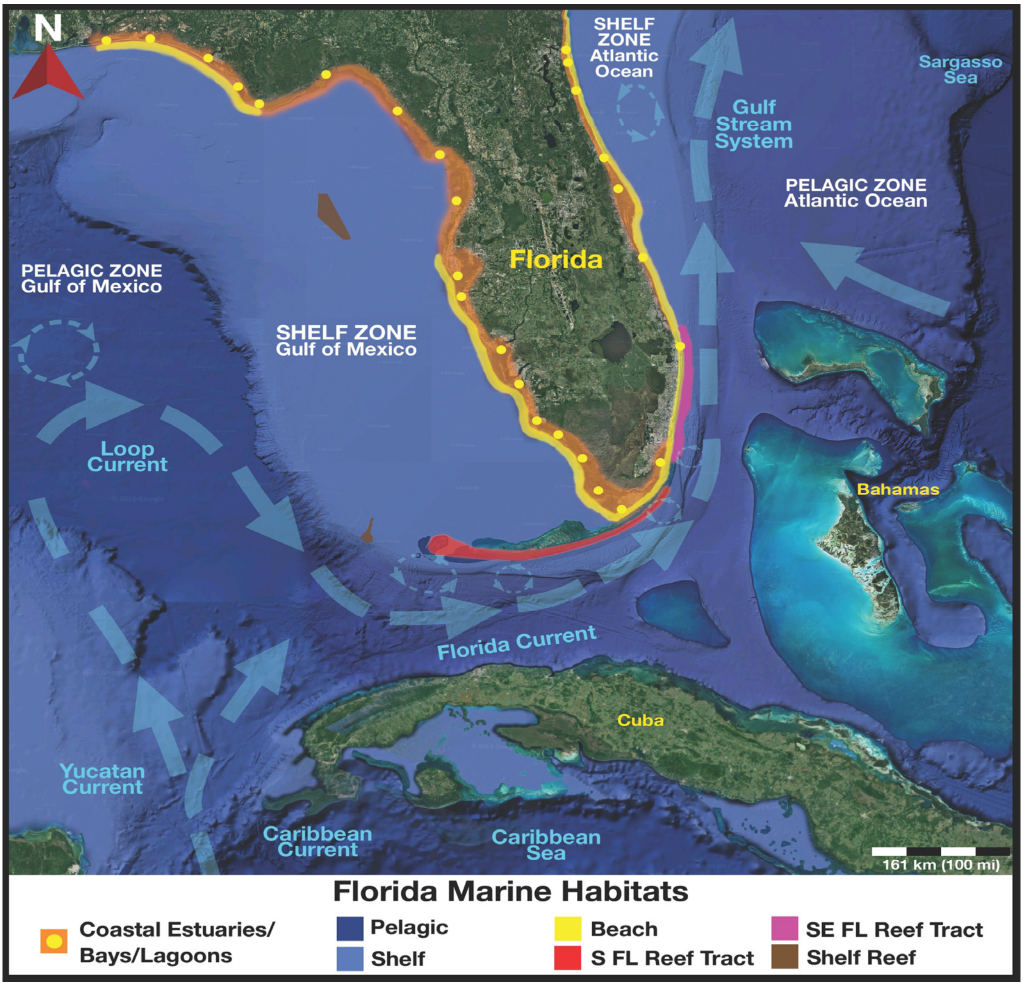

Figure 13.7. Map depicting five broad Florida marine habitats across the landscape and seascape including Coastal Estuaries, Bays and Lagoons, Pelagic and Shelf Zones, Beaches and South and Southeast Florida Reef tracts and western shelf reefs (e.g., Florida Middle Ground [northwest shelf], Pulley Ridge [southwest shelf]). Regional current systems that are important drivers of marine habitats in Florida are also depicted (defined in Fig. 13.1). Northwest to northeast the following Estuaries, Bays and Lagoons are identified by yellow circles: Pensacola Bay, Choctawhatchee Bay, Grand Lagoon, St Joseph Bay, Apalachicola Bay, Apalachee Bay, Deadman Bay, Waccasassa Bay, Homosassa Bay, Tampa Bay, Sarasota Bay, Charlotte Harbor, Estero Bay, Rookery Bay, Fakahatchee Bay, Chokoloskee Bay, White Water Bay, Florida Bay, Biscayne Bay, Lake Worth Lagoon, Indian River Lagoon, Banana River, Mosquito Lagoon, Matanzas River, Guana River, Saint Johns River. *Illustration credit: Chris Johnson. Image credit: Google Maps.*

Coastal Estuarine, Bay and Lagoon Habitats

Florida's peninsula geography and low-lying coastline create extensive networks of shallow estuaries, bays, and lagoons (Fig. 13.7). These include Pensacola Bay, Apalachicola Bay and Grand Lagoon along the panhandle in the northern Gulf of Mexico; Tampa Bay, Charlotte Harbor, and Rookery Bay along the western peninsula; White Water Bay, Florida Bay and Biscayne Bay at the southern tip of the peninsula; and long linear lagoon systems interior of barrier islands, Lake Worth Lagoon, Indian River Lagoon and Mosquito Lagoon along the eastern seaboard, representative of the hundreds of coastal systems encircling the state. Maintenance of the foundation communities within these habitats, salt marshes, in upper reaches of the state influenced by continental temperatures, mangroves in the southern subtropical regions, and oyster reefs in mesohaline (intermediate salinity) estuaries, is critical in order to preserve the highly productive marine habitats of Florida's coastline. Coastal estuaries, bays, and lagoons provide ecosystem services for human populations, including primary productivity that supports fisheries production, three-dimensional habitat structure, and improved water quality through sediment deposition and nutrient uptake. Organic matter and nutrient recycling support microbial- or algal-based food webs, both within the coastal ecosystems and adjacent pelagic ecosystems through transient marine species of ecological and economic importance, for example tarpon, grouper, mackerel, snapper, pink shrimp and lobster (Ault et al. 2005; Lellis-Dibble et al. 2008; Ault et al. 2014). Mangroves and saltmarshes also attenuate storm surge and lessen wave and flooding impacts on coastal built infrastructure along Florida's coastline (Zhang et al. 2012). Estuaries and lagoons provide recreational opportunities, e.g., boating and fishing, that add to Florida's economy (Ault et al. 2005; FOA 2013). Seagrass ecosystems are recognized for their nursery role in the development of juvenile fish and shellfish, and for provide forage grounds for endangered, threatened and at risk marine species, including manatees, queen conch, sea turtles and sharks (Heck et al. 2003; Ault et al. 2014).

Reef Habitats

In contrast to soft-bottom sedimentary environments, reef habitats are formed on hard-bottom substrate, primarily carbonate platforms and matrices. Florida reefs form along 580 km of coast from the Dry Tortugas on the shelf, around the southern peninsula, and half-way up the southeast coast to 27° 10'N (Fig. 13.7). Although geographically contiguous, the origin and formations of these reefs are quite distinct. The South Florida Reef Tract is the second longest (240 kilometers) offshore bank-barrier reef system in the world, extending from Biscayne Bay to the Tortugas Banks and dominated by reef-building (hermatypic) corals (Fig. 13.8). Florida's barrier reef is generally composed of an inner and outer ridge parallel to the Florida Keys (Lidz et al. 2003 2006). Patch reefs and seagrass meadows develop on the interior banks underlain by carbonate sedimentary features of the Holocene (~5,000 bp). Outer reefs are composed of narrow coral ridge-and-swale structures established on Pleistocene coral bedrock. The hermatypic reef-building stony corals on the barrier reef are slow growing, but have kept pace with sea level rise during the last 6,000 years, shifting community composition in response to wave energy (Lidz et al. 2006).

The southeast Florida continental reef tract (~1450 km^2) along the eastern peninsula of Florida (Fig. 13.8) sustains a high biodiversity of corals, sponges, and other marine benthic organisms. While not reef building, due to a minimal presence reef-building corals and other physiographic conditions, contemporary southeast reefs create important habitats. For example, they are within the *Acropora* sp. critical zone, an important endangered reef-building coral in the Caribbean (Wirt et al. 2013), and provide habitat for the highly endangered hawksbill turtle (Wood et al. 2013) in addition to a wide range of fish, shellfish, sharks, rays, and marine mammal species. The southeastern Florida reef system is composed of outer, middle, and inner relict reef terraces (Precht and Aronson 2004), with only the outer reef extending northward to Palm Beach County. The southern reefs indicate distinct spur and groove characteristics (Dade and Broward counties) and may have been continuous with the southern Florida Reef Tract. However, southeast reefs appear to have formed on dune ridges (Stathakopoulos and Riegl 2015) parallel to the Florida shoreline (Banks et al. 2007) in contrast to the southern Florida Reef Tract that underlies Pleistocene coral reefs. Southeastern corals also established on platforms built by Sabellariid marine worms or polychaetes through the consolidation of sands and carbonate shells. In addition to their ecological value, the Florida continental reef tract supports an active diving and sports fishery industry in the coastal counties of southeast Florida (FOA 2013).

Along Florida's West Coast discontinuous reefs are found on ledges and outcrops on the Florida shelf, one of the largest carbonate platforms on earth (~225,000 km^2). A recent review of benthic data from the shelf by Jaap (2015) indicates that, while not as speciose and continuous as southern platform reefs, the benthic communities of the western shelf represent a complex mosaic of corals and other benthic organisms (e.g., sponges, hydrozoans, macroalgae, molluscs). These reef systems develop on pinnacles and outcroppings of carbonate constructed by vermetid gastropods over sand ridges ~8,000 years ago (Reich et al. 2013; Jaap 2015). Some of these sites, such as the Florida Middle Ground reef (28°35'N) and Pulley Ridge, have high biodiversity and a complex structure that contributes to high secondary fisheries production in a relatively low productivity shelf environment (Jaap 2015), thus also having a high ecological and economic value.

Pelagic and Shelf Habitats

Florida's pelagic and shelf habitats in the Gulf of Mexico and Atlantic Ocean are coupled through regional currents, including the Caribbean, Yucatan, Loop, Florida and Gulf Stream complex. Regional currents affect the transport of nutrients and plankton that support secondary production and larvae for finfish, shellfish and invertebrates. Currents are also critical in establishing larval recruitment into coastal estuarine, bay, lagoon, reef, and shelf habitats. Upwelling of deep nutrient-rich water onto the Florida shelf from pelagic zones (<150 m) is influenced by the Loop Current and its eddies. This depends on current proximity and strength along the Florida shelf slope (Weisberg et al. 2016) and upwelling associated with mixing of deep layers under cooler surface water temperatures. The inter-annual mixing of new nutrients with isolated oligotrophic (low nutrient) shelf water (Dixon et al. 2014) enhances primary production above the modest production rates driven by local wind-driven mixing (Weisberg et al. 2016) and entrainment of riverine nutrient flux, particularly from the Mississippi River plume, which also interacts with Loop Current eddies (Jones and Wiggert 2015). High fisheries production on the oligotrophic Florida shelf habitat depends on nutrient subsidy primarily driven by the Loop Current across the shelf slope. Cooler temperatures during the winter months are associated with deeper mixed layers that mix high nutrient deep water with surface waters leading to enhanced surface chlorophyll concentrations (Muller-Karger et al. 2015).

Along the Atlantic Shelf, the southern extent of the South Atlantic Bight (Fig. 13.1), nutrients are upwelled along the shelf break. Nutrient transport is primarily driven by eddies, meanders and subsurface intrusions of the Gulf Stream complex toward the shelf (Fig. 13.8; Lee et al. 1991). These short, but significant, nutrient pulses support primary production and account for high secondary production along the eastern Florida shelf (Fiechter and Mooers 2007). The South Atlantic Bight is considered a low-nutrient shelf where phytoplankton rely on nutrients from rivers and the high-magnitude nutrient pulses propelled by Gulf Stream dynamics (Yoder et al. 1983; Miles and He 2010). Thus, on both the east and west Florida shelves, primary productivity is linked to regional currents and eddies upwelling nutrient-enriched subsurface water.

The deeper pelagic zones of the Gulf of Mexico and Atlantic Ocean not only provide nutrients in support of shelf primary and secondary productivity, but represent critical spawning grounds for large pelagic fish with high commercial value, for example tuna (Muhling et al. 2013). The Gulf of Mexico contains spawning grounds for tuna, mackerels, billfishes and other important commercial and sport fisheries. Studies of larval stages of these fish from the Florida Current indicate they are close to 100% satiated (no empty guts) compared to other regions of the world (Gulf of California; Northwest Australia) (Llopiz and Hobday 2014). The Loop-Florida-Gulf Stream Current system, with its complex oceanographic eddies, waves and meanders, represents fundamental recruitment mechanisms that sustain Florida marine habitats' high biodiversity and productivity (Lee et al. 1991). Loop Current eddies transport tropical invertebrate larvae, including corals, into the continentally-influenced cooler waters in the northern Gulf of Mexico, for example the Florida Middle Ground Reefs (Fig. 13.8; Reich et al. 2013). Frontal eddies of the Florida Current also coincide with multi-taxa (29 fish families) larval coral reef fish recruitment in the upper Keys (Sponaugle et al. 2005) from spawning sites in the Dry Tortugas (Lee and Williams 1999). Reef fish larvae entrained into eddies along the Florida Current exhibit higher growth rates due to greater resource availability, which ultimately correspond to high survival rates and recruitment onto the reef (Shulzitski et al. 2016). There is new evidence that even large game fish (permit) are recruited from local spawning sites in the southern Keys (Dry Tortugas region) rather than from spawning locations within the Caribbean (Bryan et al. 2015). In Florida, spawning aggregation sites (Tortuga and Pulley Ridge reefs) appear to be critical for reef fish self-recruitment (Cowen and Sponaugle 2009; Ault et al. 2014), thus population sustainability is dependent on current entrainment eddies (Bryan et al. 2015) rather than long-distance dispersal.

Similar to Loop and Florida currents, the Gulf Stream intrusions and frontal zone eddies along the west Florida Atlantic shelf support high phytoplankton, zooplankton, and larval fish abundances with enhanced growth rates (Yoder et al. 1983; Govoni et al. 2009). Eddies with associated upwelling of deep water provide nutrients to support rapid development of larval fish and time for development through retention that increase survival and retain populations proximate to juvenile and adult foraging grounds (Yoder et al. 1983; Govoni et al. 2009). Therefore, while the pelagic zones themselves (for example, the central Gulf of Mexico or Gulf Stream) are low in nutrients and primary productivity, eddies generated from the Loop Current in the Gulf of Mexico and the Florida Current and Gulf Stream circumnavigating Florida promote highly productive fisheries habitats along Florida's coastal zones.

Pelagic currents also assist in the transport of larval and juvenile tropical organisms throughout the subtropics and temperate regions, including sea turtle hatchlings that utilize the Sargasso Sea gyre (Figs. 13.1, 13.8) for trans-Atlantic transport during development (Putman et al. 2010). Hatchlings are entrained into wracks of floating *Sargasssum* seaweed, which provide them with food and protection as they are transported to western Atlantic foraging sites (e.g., Azores).

Beach Habitats

Once adults, sea turtles migrate back to the beach where they hatched. Loggerhead, green, and leatherback turtles nest on Florida beaches across the entire coastal zone of the state, with the exception of the Big Bend area (Fig. 13.7). Florida beaches provide 80% of the nesting sites of loggerhead sea turtles in the US. Sustaining sea turtle populations, including the rare and endangered green, Kemp's ridley, and hawksbill turtle, is a state and national priority. Preserving beaches in Florida is critical not only for endangered sea turtles, but also to protect one of the most important economic sectors of Florida's economy, tourism (FOC 2013). The value of beaches is enhanced by the presence of sea turtle nesting and residents are committed to their conservation (Hamed et al. 2016).

Consequences of Climate Change for Florida's Marine Habitats

Major Drivers of Change

The highly diverse and productive marine habitats of Florida, and their associated ecosystem services, are threatened by climate change impacts (Fig. 13.8). In this section, dominant drivers of climate change are discussed along with their impacts on Florida habitats. The major direct climate change drivers that presently and will continue to degrade Florida's marine habitats are (1) accelerated rates of sea level rise, (2) increasing ocean temperatures, and (3) ocean acidification. These primary drivers lead to secondary changes that further degrade habitats. Increasing ocean temperatures lead to (4) low oxygen levels in surface waters or hypoxia. Higher evaporation rates with greater atmospheric warming raises the (5) sea surface salinity, which stresses organisms because they must utilize metabolic energy for osmoregulation rather than for growth or reproduction. Rapid sea level rise results in (6) coastal erosion with primary effects on coastlines and their associated habitats, such as beaches, lagoons and estuaries. Under coastal erosion, sediment and nutrient loads increase, leading to turbidity and (7) low light transmittance to benthic (bottom dwelling) communities that require high light (e.g., seagrasses and coral reefs). At the broader scale, (8) changes in current patterns and flow rates will significantly modify Florida marine habitats and their primary and secondary productivity.

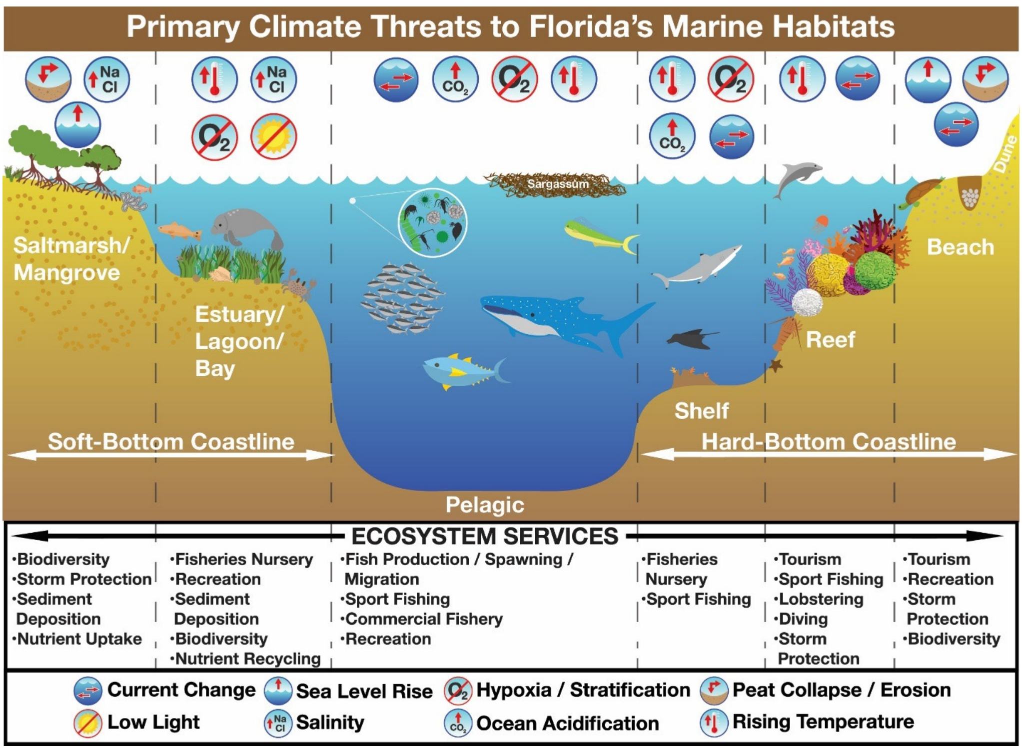

Figure 13.8. Illustration of the large-scale marine habitats of Florida and the primary drivers that threaten their sustainability and ecosystem services under climate change. *Illustration credit: Chris Johnson.*

Coastal Wetlands and Beach Shorelines

Mangrove forests and salt marshes represent the transition zone between terrestrial and aquatic systems where they buffer waves and storm surges for upland areas and filter land sediment and nutrients to adjacent estuaries, lagoons, and bays. These ecosystem services, along with high biodiversity, are primarily threatened by high rates of sea level rise, particularly in locations around Florida where migration inland is not an option because of human development.

Developments and infrastructure will also be subject to greater coastal hazards without coastal wetlands (FOCC 2010; Geselbracht et al. 2015). The predicted rates of sea level rise globally and in Florida are based on different scenarios of global greenhouse gas mitigation measures with the low range assuming strong mitigation measures and the high range reflecting the "business as usual" scenario. The current unified sea level rise predictions for Florida are 6-10 inches (15.2-25.4 cm; 4-7 mm y^{-1}) by 2030, 14-26 inches (35.6-66.0 cm; 5-10 mm y^{-1}) by 2060, and 31-61 inches (78.7-154.9 cm; 7-14 mm y^{-1}) by 2100, with less certainty as the rates are projected further in time (SFRCCC 2015).

Models of coastal wetland loss using vegetation and elevation maps for Florida were used to forecast sea level rise effects on six major Florida estuaries along the Gulf of Mexico: Pensacola Bay, St. Andrews/Choctawhatchee Bays, Apalachicola Bay, Southern Big Bend, Tampa Bay, and Charlotte Harbor (Geselbracht et al. 2015). This assessment showed that urban areas (Tampa Bay and Charlotte Harbor) lost a higher percentage of wetlands (~15K hectares; 15-20%) and almost a complete loss of tidal flats and freshwater marsh, under 1 m (100 cm) of sea level rise. Where wetlands had the opportunity to move upslope, less total wetlands were lost but shifts in wetland communities occurred. For example, in Pensacola Bay, Apalachicola Bay, and the Southern Big Bend region, 44-80% of tidal swamp (0.3-3K ha) and 18-49% of coastal forest (10-25K hectares) were replaced by tidal flats, brackish/salt marsh, and estuarine beach shorelines under 1 m of sea level rise (Geselbracht et al. 2015). This analysis suggests that if area is available around the Florida coastline, wetland species may shift, but retain many of their ecosystem services.

In coastal areas with low elevation gradients, for example South Florida with less than 4.5 cm km^{-1} from the mangroves through the Everglades' marsh to Lake Okeechobee (~100 miles; 160 km), coastal mangroves and marshes are likely to be overwhelmed by a rapid rate of sea level rise (> 5 mm y^{-1}; Koch et al. 2015). They can, however, keep pace with modest rates of sea level rise. Florida's recent (last ~100 years) sea level rise rates of 2.14 ± 0.03 mm y^{-1}, estimated using 26 gauges across Florida's coastline (Bâki et al. 2012), are similar to earlier estimates of 1.5 to 2.4 mm y^{-1} using tide gauge data (Maul and Martin 1993) and compare closely with regional altimetry-based estimates of 1.5 to 1.7 ± 0.3-0.6 mm y^{-1} (Bâki et al. 2012; Palanisamy et al. 2012). At these relatively slow rates of rise, belowground biomass of saltmarsh and mangrove vegetation contributes to inorganic sediment deposition and keeps pace with sea level changes, illustrating the importance of a biological feedback in this habitat (McKee et al. 2007; McKee 2011; Alizad et al. 2016). Promoting organic matter accumulation is enhanced by minimizing other stressors, such as hypersalinity with freshwater enhancement. Peat loss of mangrove sediments in the Caribbean and Florida can also be subject to non-linear "collapse" or erosion following tropical storms when vegetation is compromised (Wanless et al. 1994). Thus, sustaining vegetation is critical to promote positive elevation change along Florida's wetland coastline. Although accretion and erosional processes occur, mangroves in Florida and the wider Caribbean have kept pace with sea level rise rates of 2-4 mm y^{-1} over thousands of years, but not

5 mm y^{-1} (Koch et al. 2015), and modeling studies of salt marshes in northeast Florida indicate that overall marsh biomass density increases at 3.1 mm yr^{-1} (11 cm by 2050) but declines at 13.7 mm y^{-1} (48 cm by 2050, Alizad et al. 2016). These data highlight the importance of global mitigation of climate warming to maintain Florida's sea level rise at the lowest projections and relatively stable present shoreline. This point is critical, as even the upper unified Florida projections for 2030 equate to 7 mm y^{-1}, assuming linearity of rise, which would likely drown coastal wetlands with no potential for shoreward expansion or shallow elevation gradients. Further, many of the wetlands in Florida developed in quiescent waters interior of coastal carbonate reef or sand barrier systems that are also subject to erosion as sea levels rise.

Beach Shorelines

Beach mainland and barrier islands are subject to sand migration in response to local hydrodynamics, prevailing currents, counter currents, and wave profiles (Finkl and Makowski 2013). Along Florida's East and West coasts as well as the Panhandle, sand-dominated shorelines are dynamic, requiring input of sands to maintain a static position of Florida's coastline (Dean and Houston 2016). Stronger tropical cyclones and a rise in sea levels predicted with increasing sea surface temperatures have the potential to destabilize shorelines. The dynamic nature of Florida's beach shorelines that reside on bedrock or migrating sands results in a high sea level rise vulnerability of beach habitats on which sea turtles and many coastal human residents depend. Based on an analysis of the dominant sea turtle nesting in Florida, the loggerhead turtle, ~43% of beach nesting is predicted to be lost with a 50 cm increase in sea level by 2050 (Reece et al. 2013). This sea turtle species and others are predicted to shift northward to accommodate high temperatures that negatively influence a balance of sex ratios and successful reproduction (Witt et al. 2010). Hard armoring of dynamic shorelines, contraction of land available for human settlement, and erosion of beaches may constrain sea turtle nesting in alternative suitable locations to adapt to climate change, as they have done over evolutionary (100 million years) time scales (Reece et al. 2005; Witt et al. 2010). The rates of change are likely to limit sea turtles' ability to respond because they are a long-lived species (80-100 years) and have site fidelity to beach nesting sites adjacent to urban development throughout Florida.

Coastal Estuaries, Bays and Lagoons – Open Water Systems

Estuaries, bays, and lagoons encompass Florida's coastline (Fig. 13.7) and sustain a sport fishing, boating, and tourist economy worth more than one billion dollars. This economy depends on "healthy" seagrass ecosystems. The three-dimensional structure and high primary productivity of seagrasses transform a depauperate bare bottom estuary, lagoon or bay into a highly biodiverse habitat for invertebrates (e.g., lobsters, conch, crabs, oysters) and larval/juvenile fish (e.g., seatrout, mullet, bonefish, sheepshead, red drum, tarpon), and provide foraging grounds for sea turtles, manatees, dolphin, and elasmobranchs (rays, sharks). Globally, estuarine and lagoon seagrass ecosystems are threatened by poor water quality that reduces the light reaching the benthos (Orth et al. 2006), principally from upland non-point sources of nutrients and sediments. Seagrasses stabilize the sediment and provide organic matter to infauna (clams, shrimp, worms) with their large proportion of belowground biomass; but this non-photosynthetic tissue has a high metabolic demand, necessitating a high light environment (4-30% of surface light levels; Duarte 1991 ; Dennison et al. 1993). Thus, as sea levels rise and coastal erosion and nutrient fluxes increase, seagrasses across the state will be exposed to lower light, degrading ecosystem services presently provided by these ecosystems (Fig. 13.9).

Given Florida's broad coastal ocean temperature range (seasonal average range = 10-30 ºC; 50-87 ºF), increases of 1-4 ºC above maximum average temperatures to ~31-34 ºC are within the physiological limits of tropical seagrasses (Koch et al. 2013). Under these conditions, seagrass species in North Florida may shift to tropical species, but direct effects will likely be tolerable. However, ocean warming also results in high salinity (evaporation) and lower oxygen solubility, which causes physiological stress to vegetation, increases root exposure to sulfide, a known phytotoxin (Koch et al. 2007), and limits the ability of estuaries and lagoons to serve as viable fish habitats, particularly in lagoons and estuaries with restricted circulation and long water residence times. Florida Bay, one of the largest (1,000 square miles; 2,600 km^2) and most productive estuaries in Florida that supports important fisheries (e.g., pink shrimp, stone crab, spiny lobster, bone fish) and associated industries (sport fishing, tourism), has succumbed to large-scale seagrass die-off (~10,000 ha; 25K acres) and fish mortality events over the last few decades (Hall et al. 2016). These mortality events have been attributed to hypoxia and sulfide production driven by warm, hypersaline waters in this shallow seagrass-dominated ecosystem (Koch et al. 2007; Hall et al. 2016). The Florida Bay case study represents a precursor for estuaries around the state that are building up biomass (seagrass, algae and phytoplankton) under coastal nutrient enrichment leading to a high oxygen demand. Increased thermal loads and erosion with climate change will further exacerbate this problem statewide. Based on downscaled climate models, coastal estuaries and bays along Florida's northwest coast may encounter the greatest rise in temperature (3-4 ºC by 2100). This localized warming along the West Florida coast is a consequence of stratification and reduced upwelling as the Loop Current and AMOC weaken (Liu et al. 2015). High ocean temperatures and enhanced nutrient enrichment synergistically promote hypoxia and foster harmful algal blooms (primarily cyanobacteria and dinoflagellates) in coastal systems causing fish kills and human health concerns (Paerl and Paul 2012). Harmful algal blooms are already an issue for human health and fisheries along Florida's West Coast and in Florida Bay (Weisberg et al. 2016; Berry et al. 2015).

Hard-armoring of shorelines in Florida to protect human infrastructure from sea level rise is also likely to restrict the connectivity between wetlands and estuaries, bays, and lagoons. Without wetland buffers, pulsed nutrients and sediment loads to coastal water bodies are likely to increase. Loss of wetlands also and eliminate an important larval to juvenile fish and shellfish habitat, further reducing fisheries production potential in these coastal ecosystems (Gittman et al. 2016).

Coral Reefs

Ocean Warming

Coral reefs worldwide are negatively affected by stressors at the local and global scale, ushering in the current age of corals: “Conservation or Extinction” (Hixon 2011). Widespread local stressors (siltation, pollution, eutrophication, disease, exotics and overfishing) that have been driving reef decline over the last few decades globally (Jackson et al. 2014) and in Florida (Ault et al. 2005; Kruczynski and Fletcher 2012) are now compounded by coral thermal bleaching in response to warming oceans under climate change (Jackson et al. 2014). A massive coral reef die-off (80% bleaching; 40% mortality) in response to a modest rise in temperature (+1.2 ºC) throughout the wider Caribbean during the ENSO event of 2005 (Eakin et al. 2010) and the present 81% coral beaching on the northern Great Barrier Reef in 2016 (CCOA 2016) illustrate the thermal sensitivity of corals residing at their upper thermal limits. Degree heating weeks (DHWs), an index used for regional assessments of thermally-induced coral bleaching (loss of symbiotic algae), has been used to assess bleaching probabilities and reef decline. At eight DHWs, corals reached a threshold of annual severe bleaching (ASB) that results in mortality (Frieler et al. 2012) unless acclimation or adaptation ensues. Based on SST predictions (RCP 8.5) applying low resolution, climate models (33 CMIP 5 ensemble) and dynamically downscaled (MOM4.1, ~11 km) or statistical models were used to define the year that ASB would be reached across the wider Caribbean (3781 reef locations), including Florida (van Hooidonk et al. 2015). Regardless of models used or the downscaling approach, ASB was predicted to be reached by 2040 to 2043 ± 10 years at the broad regional scale and all reef locations by 2070. Dynamically downscaled models that incorporate local-scale hydrodynamics and regional current systems exhibit high temporal variability. For example, on the southern Florida Reef Tract, western reefs are predicted to experience ASB by late 2020 compared to the early 2050s for eastern reefs in response to slowing of the Gulf Stream System and Loop Current. Downscaled models also identify regions for transient coral refugia against severe bleaching, which may allow some corals to survive and more slowly adapt to rising temperatures. Coral refugia from thermal stress would also occur along Florida’s southeastern Reef Tract and on solitary shelf reefs in deeper waters, but larval transport to the southern Florida Reef Tract may be limited by prevailing currents eastward and reduced excursions of the Loop Current into the Gulf of Mexico, respectively.

Elevated temperatures and stressed corals from thermal bleaching may also promote coral diseases that have already decimated reef-building corals in Florida and the wider Caribbean region over the last few decades (Weil and Rogers 2011). Specifically, a virulent outbreak of white band disease caused mass mortality of the *Acroporas* (*palmata* and *cervicornis*; Gladfelter 1982), which have not recovered within the southern Florida Reef Tract, although individuals are found amongst the three reef habitats discussed herein. As microbial activity increases with temperature, particularly when organisms are stressed, ocean warming could drive greater pathogenic activity on Florida’s reefs.

Ocean Acidification

In addition to causing ocean warming, CO_2 in the atmosphere is dissolving into and reacting with seawater leading to a lower ocean pH called "ocean acidification" (OA). The effect of OA on coral calcification has been the focus of intense research over the last decade. Based on this research, some coral species and locations have been shown to be more resilient to OA than others (Shamberger et al. 2014; Barkley et al. 2015) making generalizations on the effects of OA on coral calcification challenging. Some corals acquire the energetics to calcify even at a low pH predicted for 2100 (pH ~7.8). However, these corals are subject to greater bioerosion (Manzello et al. 2008; Barkley et al. 2015). In Florida's southern Reef Tract, seagrass sequestration of CO_2 in reef lagoons has provided seasonal resilience to OA for interior patch reef corals (Manzello et al. 2012). At a broad scale, high net ecosystem metabolism in coastal ecosystems of Florida, particularly with high seagrass biomass and under nutrient enrichment, exhibit highly seasonal and daily changes in pH (Millero et al. 2001; Yates and Halley 2006; Manzello et al. 2012) that dwarf open ocean estimates of pH decline from OA (Bates et al. 2012). Determining the effect of OA on net calcification at the reef scale provides the ability to ascertain reef ecosystem potential to build structure and keep pace with sea level rise (Andersson and Gledhill 2013). Reef building is currently uncertain across the southern Florida Reef Tract based on evidence of erosional or modest rates of calcium carbonate deposition (Muehllehner et al. 2016) and significant declines in reef building corals over the last few decades (Ruzicka et al. 2013) from 1996-2009 (CREMP, 2012). Further, there is evidence that corals that build carbonates are being replaced in part by bioeroders of the reef framework (e.g., sponges, urchins, mollusks; Muehllehner et al. 2016).

Reef Fisheries

As coral and other marine organisms possess planktonic early life stages, and recruitment is local or self-recruiting, population sustainability will be reliant on local current systems (Cowen et al. 2000). Recruitment is essential in the southern Florida Reef Tract given target fisheries, such as snapper, grouper, grunts, jacks progies, and hogfish, have all been exhaustively exploited for 85 years (Ault et al. 2005). Further, reef fish are sensitive to extraction and loss of reef structure and adjacent habitats, including the coral-seagrass-mangrove complex. In Florida, eddies associated with coastal currents transport larval invertebrates, including coral, shrimp, and fish from local spawning grounds (e.g., Tortugas, Pulley Ridge Reefs) to Florida Reef Tracts (Lee and Williams 1999; Sponaugle et al. 2005; Ault et al. 2014; Shulzitski et al. 2016; Vaz et al. 2016) and local estuaries (e.g., Florida Bay pink shrimp; Criales et al. 2007). Thus, predictions of a slowing AMOC and Gulf Stream system under climate change that reduce the Florida and Loop currents by 25% and weaken accompanying gyres (Liu et al. 2015) are likely to have wide-ranging consequences for population dynamics, fisheries management, and overall secondary productivity of Florida's coral reefs and associated estuary, bay, and lagoon ecosystems. While Florida reef recruitment from the wider Caribbean may be limited for some species, albeit still significant for others (e.g., spiny lobster; Kough et al. 2013), limited larval entrainment from Caribbean and Yucatan current systems could constrain genetic diversity and resilience in populations over longer time scales.

Pelagic and Shelf

Phytoplankton Production and Harmful Algal Blooms

Florida's shelf and pelagic habitats have been subject to multiple stressors over the last few decades, shifting how these ecosystems function and modifying their conceivable response to climate change. Primary amongst these is overfishing of target piscivore fish species (e.g., red snapper, grouper and mackerel) on Florida's western shelf (Walsh et al. 2011). The systematic removal of predatory pressure on zooplankton-grazing fish (clupeoid sardine, herring, anchovy, and menhaden), shrimp, jelly fish and other grazers depressed zooplankton ten-fold (1973-1993) on the shelf and likely contributed to a reduction in zooplankton grazers (pink shrimp) as their prey was diminished (Walsh et al. 2011; Muhling et al. 2012). In the absence of zooplankton, phytoplankton increased along the West Florida Shelf, including harmful algal blooms that negatively affect marine organisms and human health and a food web perturbation observed globally (Landsberg et al. 2009; Walsh et al. 2012).

Under ocean warming and a reduction of nutrient flux across the Florida shelves, and as the Loop Current excursions into the Gulf of Mexico subside, harmful algal blooms will continue to be favored. Harmful algal species competitively dominate the phytoplankton community under low-nutrient stratified conditions promoted by increased warming, which are predicted to be greatest along the west Florida Shelf (Liu et al. 2015) where harmful algal blooms dominate (Landsberg et al. 2009). Further, lack of upwelling of Loop or Florida (Gulf Stream) currents via eddies and other transgressions along the Florida shelves will diminish deep nutrient sources to the shelf (Weisburg et al. 2014) selecting for low-nutrient adapted harmful algal bloom species. Finally, harmful algal bloom development with greater toxin potency, including saxitoxin dangerous for humans, has been linked to low nutrient conditions (Walsh et al. 2011). If nutrient limitation on the Florida shelves accompanies climate change due to a reduction of the Loop and Florida currents, the Florida shelves and South Atlantic Bight are likely to depend on wind-induced upwelling and riverine sources, becoming a less productive fisheries habitat.

Pelagic Fish Spawning

In the open pelagic realm of the Gulf of Mexico, modest ocean warming predictions from downscaled models (MOM4) indicate changes in distributions and reproduction of commercially important pelagic fish species such as Atlantic bluefin, yellowfin, and skipjack tuna (Muhling et al. 2015). The temperate Atlantic bluefin tuna is most at risk from climate change because of its low adult and larval thermal thresholds (28-29 and 26ºC, respectively) and restricted spawning habitat in the Gulf of Mexico, which is predicted to be unsuitable for adults or larval stages by 2090 (RCP 8.5; Muhling et al. 2015). The wider-ranging tropical tuna species, yellowfin and skipjack, are predicted to replace Atlantic bluefin and expand their range (Muhling et al. 2015) into the Gulf of Mexico as temperate waters warm to 30-32 ºC (>16 ºC), temperature ranges where they are currently found (Boyce et al. 2008). These model scenarios predict a loss of bluefin tuna and a shift to tropical tuna species in the Gulf of Mexico and Florida Current; however, bluefin tuna accommodate surface water hypoxia and high temperature by residing in deeper waters (Muhling et al. 2015), which may provide a short-term strategy for adapting to rapid temperature increases in the Gulf of Mexico, particularly the northern Gulf, which may warm more slowly as the Loop Current incursions subside.

Ocean Acidification

The scale of atmospheric CO_2 invasion into oceans is staggering at a current rate of 1-3.2 billion (10^9) metric tons C y^{-1} (1-3.2 petagrams [10^{15} g] C y^{-1}), equating to 155 cumulative billion tons of C over the last 250 years (1750-2010) with another ~400 billion tons of C to be added by 2100 (2012-2100) without atmospheric CO_2 mitigation (RCP 8.5; IPCC 2013). Elevated CO_2 concentrations in seawater can constrain highly mobile marine organisms with high metabolic rates thorough hypercapnia acidosis (Pörtner et al. 2004) or directly affect development, as was recently found for yellowfin tuna (Frommel et al. 2016). Other calcifiers in the plankton including calcified molluscs (pteropods) and phytoplankton (coccolithophores) widely distributed in the Gulf of Mexico and Atlantic have shown sensitivity to OA in temperate oceans (Fabry et al. 2008; Guinotte and Fabry 2008). Changes in ocean chemistry with respect to atmospheric CO_2 sequestration, and OA were examined in a synoptic cruise along the Gulf of Mexico shelf and eastern seaboard of the United States in 2007 and again in 2012 (Wang et al. 2013; Wanninkhof et al. 2015). Cruise data indicated that the highly buffered water (high alkalinity that resists OA) from the Loop Current and Gulf Stream presently maintains a high saturation state for calcium carbonate (Ω) in surface waters of the Gulf of Mexico and Florida Shelf (Wang et al. 2013). All measurements indicated that shelf waters were supersaturated with respect to the aragonite carbonate mineral ($\Omega_A > 1$), inferring mineral stability rather than dissolution. Thus, today the subtropical surface waters around Florida's shelf and open water are relatively well buffered from OA in contrast to temperate and polar oceans, and undersaturated deep waters (Wang et al. 2013; IPCC-AR5 2013).

In a future without significant mitigation of atmospheric CO_2 emissions (RCP8.5), however, carbonate saturation states will be undersaturated (<1 Ω) by 2050 in the Arctic and Southern Ocean and 2150 in the tropics (IPCC-AR5 2013). Thus, tropical/subtropical oceans will buffer Florida's shelf and pelagic habitats in the short term from corrosive waters. While this is relatively positive, low pH and Ω synergistically interact with rising temperature can affect tropical organisms before Ω becomes undersaturated. Further, because of the dominance of marine calcifiers and carbonate sediment environments in Florida habitats, the consequences of carbonate undersaturation will be stark, including dissolution of calcified organisms and release of a large pool of nutrients presently stored in carbonate sediments.

Conclusion

Florida's marine resources, already under cumulative stress, and coastal human populations are highly vulnerable to a changing climate because of the strong linkage between the state's ocean current systems (Loop, Florida, and Gulf Stream Complex), climate to global ocean circulation (AMOC) and atmospheric processes (ENSO, AMO, convection, wind shear). Predicted ocean warming will significantly affect Florida's coastline via sea level rise, as well as marine species and ecosystems due to their susceptibility to high temperatures. A 25% reduction in the Loop Current is predicted based on downscaled models to restrict warming in the Gulf of Mexico by 2100 to between 1.4ºC to 2.8ºC based on different scenarios of CO_2 mitigation, as the current will transport less warm tropical water into the Gulf than at present. However, even modest ocean warming or more extreme warming without CO_2 mitigation is predicted to have wide-ranging consequences for Florida's marine habitats (e.g., enhance coral bleaching, lower O_2 in surface waters, promote harmful algal blooms, reduce phytoplankton and fisheries production, and lower sea turtle reproduction). Further, as current systems around the peninsula of Florida entrain and transport marine organisms (e.g., fish, coral, lobster, crab, shrimp larvae and juveniles) the loss of current-driven connectivity and/or gyre systems will significantly lower the potential to sustain marine fisheries and ecosystems throughout the state. Without CO_2 mitigation at the global level, sea level rise will overwhelm wetlands along Florida's coast and lead to hard armament or retreat of human populations. Continuing to revise downscaled models and gain a more complete understanding of complex changes in air-sea interaction, large-scale currents, and the rates of climate change impacts will be critical over the next few decades to prepare and protect the state of Florida.

References

Alizad, K. et al., 2016. "A coupled, two-dimensional hydrodynamic-marsh model with biological feedback." *Ecological Modelling* 327:29–43.

Andersson, A.J. & Gledhill, D., 2011. "Ocean Acidification and Coral Reefs: Effects on Breakdown, Dissolution, and Net Ecosystem Calcification." *Annual Review of Marine Science* 5 no. 1:120717164858000.

Ault, J.S. et al., 2005. "Towards sustainable multispecies fisheries in the Florida, USE, coral reef ecosystem." *Bulletin of Marine Science* 76 no 2:28.

Ault, J.S. et al., 2014. "Indicators for assessing the ecological dynamics and sustainability of southern Florida's coral reef and coastal fisheries." *Ecological Indicators* 44:164–172.

Bâki Iz, H., Berry, L. & Koch, M., 2012. "Modeling regional sea level rise using local tide gauge data." *Journal of Geodetic Science* 2 no. 3:188–199.

Banks, K.W. et al., 2007. "Geomorphology of the Southeast Florida continental reef tract (Miami-Dade, Broward, and Palm Beach Counties, USA)." *Coral Reef* 26 no. 3:617–633.

Barkley, H.C. et al., 2015. "Changes in coral reef communities across a natural gradient in seawater pH." *Science advances*, 1 no 5: e1500328.

Baringer, M.O., and J.C. Larsen. 2001. "Sixteen years of Florida Current transport at 27 N." *Geophysical Research Letters* 28 no. 16: 3179-3182.

Bates, N.R. et al., 2012. "Detecting anthropogenic carbon dioxide uptake and ocean acidification in the North Atlantic Ocean." *Biogeosciences* 9 no. 7:2509–2522.

Berry, D.L. et al., 2015. "Shifts in Cyanobacterial Strain Dominance during the Onset of Harmful Algal Blooms in Florida Bay, USA." *Microbial Ecology* 70 no. 2:361–371.

Bove, M.C., J.J. O'Brien, J.B. Elsner, C.W. Landsea, and X. Niu. 1998. "Effect of El Niño on U.S. Landfalling Hurricanes, Revisited." *Bull. Am. Met. Soc.* 79 no. 11: 2477-2482.

Boyce, D.G., Tittensor, D.P.,Worm, B., 2008. Effects of temperature on global patterns of tuna and billfish richness.Mar. Ecol. Prog. Ser. 355, 267–276.

Bryan, D.R. et al., 2015. "Transport and connectivity modeling of larval permit from an observed spawning aggregation in the Dry Tortugas, Florida." *Environmental Biology of Fishes*, 98 no. 11:2263–2276.

Casey, K.S. and P. Cornillon. 1999. "A Comparison of Satellite and In Situ based Sea Surface Temperature Climatologies." *Journal of Climate*, 12, no. 6: 1848-1863.

CCOA. 2016. Australia's Coral Reefs Under Threat form Climate Change. Climate Council of Australia Limited ISBN: 978-0-9945973-0-4 (print) 978-0-9944926-9-2 (web) © Climate Council of Australia Ltd 2016

Cheng, W., J. C. H. Chiang, and D. Zhang, 2013. "Atlantic Meridional Overturning Circulation (AMOC) in CMIP5 models: RCP and historical simulations." *J. Climate* 26: 7187–7197.

Cowen, R.K. and S. Sponaugle, 2009. "Larval Dispersal and Marine Population Connectivity." *Annu. Rev. Mar. Sci*. 1:443–66.

Cowen, R.K. et al., 2000. "Connectivity Populations: Open or Closed?" *Science* 287 no.5454: 857–859.

Criales, M.M. et al., 2007. "Cross-shelf transport of pink shrimp larvae: Interactions of tidal currents, larval vertical migrations and internal tides." *Marine Ecology Progress Series*, 345:167–184.

Dennison, W.C., R.J. Orth, K.A. Moore, C.J. Stevenson, V. Carter, S. Kollar, P.W. Bergstrom, and R.A. Batiuk, 1993. "Assessing water quality with submersed aquatic vegetation." *Bioscience* 43 no. 2:86–89.

Dixon, L.K. et al., 2014. "Nitrogen, phosphorus and silica on the West Florida Shelf: Patterns and relationships with *Karenia* spp. occurrence." *Harmful Algae*, 38:8–19.

Duarte, C.M., 1991. "Seagrass depth limits." *Aquatic Botany* 40: 363–377.

Eakin, C.M. et al., 2010. "Caribbean corals in crisis: Record thermal stress, bleaching, and mortality in 2005." *PLoS ONE* 5 no. 11: e13969.

Enfield, D.B., A.M. Mestas-Nuñez, and P.J. Trimble, 2001. "The Atlantic multidecadal oscillation and its relation to rainfall and river flows in the continental U.S." *Geophys. Res. Lett.* 28: 2077-2080.

Eichler, T., and W. Higgins. 2006. "Climatology and ENSO-related variability of North American extratropical cyclone activity." *Journal of Climate* 19: 2076-2093.

Ezer, T., 2015. "Detecting changes in the transport of the Gulf Stream and the Atlantic overturning circulation from coastal sea level data: The extreme decline in 2009-2010 and estimated variations for 1935-2012." *Global and Planetary Change* 129:23–36.

Fabry, V. et al., 2008. "Impacts of ocean acidification on marine fauna and ecosystem processes." *ICES Journal of Marine Science* 65:414–432.

Fiechter, J. and C.N.K. Mooers, 2007. "Primary production associated with the Florida Current along the East Florida Shelf: Weekly to seasonal variability from mesoscale-resolution biophysical simulations." *Journal of Geophysical Research: Oceans* 112:1–21.

Finkl, C. and C. Makowski, 2013. "The Southeast Florida Coastal Zone (SFCZ): A Cascade of Natural, Biological, and Human-Induced Hazards." In: C.W. Finkl (ed.), Coastal Hazards, Coastal Research Library 6, DOI 10.1007/978-94-007-5234-4_1,#Springer Science+Business Media Dordrecht 2013 3.

FOA. 2013. "Florida's oceans and coasts: An economic and cluster analysis. Florida Ocean Alliance Report". www.floridaoceanalliance.org pp. 56.

FOCC. 2010. Climate Change and Sea-Level Rise in Florida: An Update of "The Effects of Climate Change on Florida's Ocean and Coastal Resources." Tallahassee, Florida. vi + 26 p. www.floridaoceanscouncil.org.

Frieler, K. et al., 2012. "Limiting global warming to 2°C is unlikely to save most coral reefs." *Nature Climate Change*, 3 no.2:165–170.

Frommel, A.Y. et al., 2016. "Ocean acidification has lethal and sub-lethal effects on larval development of yellowfin tuna, *Thunnus albacares*." *Journal of Experimental Marine Biology and Ecology* 482:18–24.

Geselbracht, L.L. et al., 2015. "Modeled sea level rise impacts on coastal ecosystems at six major estuaries on Florida's gulf coast: Implications for adaptation planning." *PLoS ONE* 10 no. 7:e0132079.

Gill, A.E., 1980. " Some simple solutions for heat-induced tropical circulation." *Quart. J. Roy. Met. Soc.*, 106: 447-462.

Gittman, R.K. et al., 2016. "Ecological Consequences of Shoreline Hardening: A Meta-Analysis." *BioScience* p.biw091.

Gladfelter W.B., 1992. "White band disease in *Acropora palmata*: impli-cations for the structure and growth of shallow reefs." *Bull Mar Sci* 32:639–643.

Gnanadesikan, A., and Coauthors, 2006. "GFDL's CM2 global coupled climate models. Part II: the baseline ocean simulation." *J. Climate*, 19:675–697.

Govoni, J.J. et al., 2009. "Mesoscale, cyclonic eddies as larval fish habitat along the southeast United States shelf: A Lagrangian description of the zooplankton community." *ICES Journal of Marine Science*, 67 no. 3:403–411.

Griffies, S. M., M. . Harrison, R. C. Pacanowski, and A. Rosati, 2004. "A technical guide to MOM4." GFDL ocean group technical report No. 5, Princeton, NJ: NOAA/Geophysical Fluid Dynamics Laboratory, 342 pp.

Guinotte, J.M. and V.J. Fabry, 2008. "Ocean acidification and its potential effects on marine ecosystems." *Annals of the New York Academy of Sciences*, 1134:320–342.

Hall, M., B.T. Furman, M. Merello, and M.J. Durako, 2016. "Recurrence of *Thalassia testudinum* seagrass die-off in Florida Bay: initial observations." *Marine Ecology Progress Series* 560:243–249.

Hamed, A., K. Madani, B. Von Holle, J. Wright, J.W. Milon, and M. Bossick, 2016. "How Much Are Floridians Willing to Pay for Protecting Sea Turtles from Sea Level Rise?" *Environmental Management* 57 no. 1:76–188.

He, R., and R.H. Weisberg. 2002. "West Florida shelf circulation and temperature budget for the 1999 spring transition." *Continental Shelf Res.* 22, no. 5: 719-748.

Heck, K.L., Hays, G. and Orth, R.J., 2003. "Critical evaluation of the nursery role hypothesis for seagrass meadows." *Marine Ecology Progress Series* 253:123–136.

Hixon, M.A., 2011. "60 Years of Coral Reef Fish Ecology: Past, Present, Future." *Bulletin of Marine Science* 87 no. 4:727–765.

IPCC, 2013. "Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change." Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex and P.M. Midgley (eds.), Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, 1535 pp, doi:10.1017/CBO9781107415324.

Jaap, W.C., 2015. "Stony coral (Milleporidae and Scleractinia) communities in the eastern Gulf of Mexico: A synopsis with insights from the Hourglass collections." *Bulletin of Marine Science* 91 no. 2:207–253.

Jackson J.B.C., M.K. Donovan, K.L. Cramer, and V.V. Lam (editors). 2014. "Status and Trends of Caribbean Coral Reefs: 1970-2012." Global Coral Reef Monitoring Network, IUCN, Gland, Switzerland.

Jones, E.B. and J.D. Wiggert, 2015. "Characterization of a high chlorophyll plume in the northeastern Gulf of Mexico." *Remote Sensing of Environment* 159:152–166.

Kennedy, A.J., M.L. Griffin, S.L. Morey, S.R. Smith, and J.J. O'Brien. 2007. "Effects of El Niño – Southern Oscillation on sea level anomalies along the Gulf of Mexico coast." *J. Geophys. Res.* 112: doi:10.1029/2006JC003904.

Knutson, T.R., McBride, J.L., Chan, J., Emanuel, K., Holland, G., Landsea, C., Held, I., Kossin, J.P., Srivastava, A.K. and Sugi, M., 2010. "Tropical cyclones and climate change." *Nature Geosci*. 3 no. 3:157-163.

Koch, M.S. et al., 2014. "Climate Change Projected Effects on Coastal Foundation Communities of the Greater Everglades Using a 2060 Scenario: Need for a New Management Paradigm." *Environmental Management* 55 no. 4:857–875.

Koch M.S., S.A. Schopmeyer, O.I. Nielsen, C. Kyhn-Hansen, and C.J. Madden, 2007. "Conceptual model of seagrass die-off in Florida Bay: links to biogeochemical processes." *J. Exp. Mar. Biol. Ecol.* 350:73–88.

Kough, A.S., C.B. Paris, and M.J. Butler IV, 2013. "Larval Connectivity and the International Management of Fisheries." *PLoS ONE* 8 no. 6: e64970.

Kruczynski, W.L. and Fletcher, P.J. 2012. "Tropical Connections: South Florida's Marine Environments." IAN Press, University of Maryland Center for Environmental Science.

Landsberg, J.H., L.J. Flewelling, and J. Naar, 2009. "*Karenia brevis* red tides, brevetoxins in the food web, and impacts on natural resources: Decadal advancements." *Harmful Algae* 8 no. 4: 598–607.

Larsen, J. C. 1992. "Transport and heat flux of the Florida current at 27 degrees N derived from cross-stream voltages and profiling data: Theory and observations." *Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences* 338, no. 1650: 169-236.

Lee, S.-K., D. B. Enfield, and C. Wang, 2007. "What drives seasonal onset and decay of the Western Hemisphere warm pool?" *J. Climate* 20: 2133-2146.

Lee, S.-K., D. B. Enfield, and C. Wang, 2011. "Future impact of differential inter-basin ocean warming on Atlantic hurricanes." *J. Climate* 24: 1264-1275.

Lee, T.N. and E. Williams, 1999. "Mean distribution and seasonal variability of coastal currents and temperature in the Florida Keys with implications for larval recruitment." *Bulletin of Marine Science* 64 no. 1:35–56.

Lee, T.N., J.A. Yoder, J.A., and L.P. Atkinson, 1991. "Gulf Stream frontal eddy influence on productivity of the southeast U.S. continental shelf." *Journal of Geophysical Research: Oceans* 96 no. C12:22191–22205.

Lellis-Dibble, K. A., K.E. McGlynn, and T.E. Bigford, 2008. "Estuarine fish and shellfish species in U.S. commercial and recreational fisheries : economic value as an incentive to protect and restore Habitat." NOAA NMFS, Office of Habitat Conservation, Habitat Protection Division.

Li, W., L. Li, M. Ting, and Y. Liu, 2012. "Intensification of Northern Hemisphere subtropical highs in a warming climate." *Nat. Geosci*., 5: 830-834.

Lidz, B.H., 2006. "Pleistocene Corals of the Florida Keys: Architects of Imposing Reefs—Why?" *Journal of Coastal Research* 224:750–759.

Lidz, B.H., C.D. Reich, and E.A. Shinn, 2003. "Regional quaternary submarine geomorphology in the Florida Keys." *Bulletin of the Geological Society of America*, 115 no. 7:845–866.

Liu, Y., S.-K. Lee, B. A. Muhling, J. T. Lamkin, and D. B. Enfield, 2012. "Significant reduction of the Loop Current in the 21st century and its impact on the Gulf of Mexico." *J. Geophys. Res*., 117: C05039.

Liu, Y., S.-K. Lee, D. B. Enfield, B. A. Muhling, J. T. Lamkin, F. E. Muller-Karger, and M. A. Roffer, 2015. "Potential impact of climate change on the Intra-Americas Sea: Part-1. A dynamic downscaling of the CMIP5 model projections." *J. Mar. Syst*. 148:56-59.

Llopiz, J.K. and A.J. Hobday, 2015. "A global comparative analysis of the feeding dynamics and environmental conditions of larval tunas, mackerels, and billfishes." *Deep-Sea Research Part II: Topical Studies in Oceanography* 113:113–124.

Manzello D.P., I.C. Enochs, N. Melo, D.K. Gledhill, and E.M. Johns, 2012. "Ocean acidification refugia of the Florida Reef Tract." *PLoS ONE* 7 no. 7:e41715.

Mapes, B. E., P. Liu, and N. Buenning, 2005. "Indian monsoon onset and the Americas midsummer drought: out-of-equilibrium responses to smooth seasonal forcing." *J. Climate*, 18:1109–1115.

Maul, G.A., and D.M. Martin,1993. "Sea-Level Rise at Key-West, Florida, 1846-1992 - America Longest Instrument Record." *Geophysical Research Letters*, 20 no. 18:1955–1958.

McKee, K.L., D.R. Cahoon, and I.C. Feller, 2007. "Caribbean mangroves adjust to rising sea level through biotic controls on change in soil elevation." *Global Ecology and Biogeography*, 16 no. 5:545–556.

McKee, K.L., 2011. "Biophysical controls on accretion and elevation change in Caribbean mangrove ecosystems." *Estuarine, Coastal and Shelf Science*, 91 no. 4:475–483.

Millero F.J., W.T. Hiscock, F. Huang, M. Roche, and J.Z. Zhang, 2001. Seasonal variation of the carbonate system in Florida Bay." *Bull. Mar. Sci*. 68:101–123.

Miles, T.N. and R. He, 2010. "Temporal and spatial variability of Chl-a and SST on the South Atlantic Bight: Revisiting with cloud-free reconstructions of MODIS satellite imagery." *Continental Shelf Research*, 30 no. 18:1951–1962.

Morey, S.L., P.J. Martin, J.J. O'Brien, A.A. Wallcraft, and J. Zavala-Hidalgo. 2003. "Export pathways for river discharged fresh water in the northern Gulf of Mexico." *J. Geophys Res.* 108. Doi: 10.1029/2002JC001674.

Morey, S.L., D.S. Dukhovskoy, and M.A. Bourassa. 2009. "Connectivity of the Apalachicola River flow variability and bio-optical oceanic properties of the northern West Florida shelf." *Cont. Shelf. Res.* 29: 1264-1275.

Muehllehner, N., C. Langdon, A. Venti, and D. Kadko, 2016. "Dynamics of carbonate chemistry, production, and calcification of the Florida Reef Tract (2009–2010): Evidence for seasonal dissolution." *Global Biogeochemical Cycles* 30 no. 5:661–688.

Muhling, B.A., J.T. Lamkin, and W.J. Richards, 2012. "Decadal-scale responses of larval fish assemblages to multiple ecosystem processes in the northern Gulf of Mexico." *Marine Ecology Progress Series* 450:37–53.

Muhling, B.A., P. Reglero, L. Ciannelli, D. Alvarez-Berastegui, F. Alemany, J.T. Lamkin, and M.A. Roffer, 2013. "Comparison between environmental characteristics of larval bluefin tuna *Thunnus thynnus* habitat in the Gulf of Mexico and western Mediterranean Sea." *Marine Ecology Progress Series*, 486:257–276.

Muller-Karger, F.E., J.P. Smith, S. Werner, R. Chen, M. Roffer, Y. Liu, B. Muhling, D. Lindo-Atichati, J. Lamkin, S. Cerdeira-Estrada, and D. Enfield. 2015. "Natural variability of surface oceanographic conditions in the offshore Gulf of Mexico." *Prog. Oceanogr.* 134: 54-76.

NOAA Office for Coastal Management, 2016. "General Coastline and Shoreline Mileage of the United States. https://coast.noaa.gov/data/docs/states/shorelines.pdf. Accessed 20 July 2016.

Oey, L.-Y., T. Ezer, and H. C. Lee, 2005. "Loop Current, rings and related circulation in the Gulf of Mexico: A review of numerical models and future challenges," in *Circulation in the Gulf of Mexico: Observations and Models,* W. Sturges and A. Lugo-Fernandez, Eds., Amer. Geophys. Union, pp. 31-56

Orth, R.J., T.J. Carruthers, W.C. Dennison, C.M. Duarte, J.W. Fourqurean, K.L. Heck, A.R. Hughes, G.A. Kendrick, W.J. Kenworthy, S. Olyarnik, and F.T. short, 2006. "A Global Crisis for Seagrass Ecosystems." *Bioscience* 56 no. 12:987–996.

Paerl, H.W., and V.J. Paul, 2012. "Climate change: links to global expansion of harmful cyanobacteria" *Water Res* 46 no.5:1349-63.

Palanisamy, H., M. Becker, B. Meyssignac, O. Henry, and A. Cazenave, 2012. "Regional sea level change and variability in the Caribbean sea since 1950." *Journal of Geodetic Science* 2 no. 2:125–133.

Peng, G., Z. Garraffo, G.R. Halliwell, O.M. Smedstad, C.S. Meinen, V. Kourafalou, and P.Hogan, 2009. "Temporal variability of the Florida Current transport at 27°N." in *Ocean Circulation and El Nino: New Research*, J.A. Long and D.S. Wells, eds. 119-137.

Pörtner, H.O., M. Langenbuch, and A. Reipschläger, 2004. "Biological Impact of Elevated Ocean CO 2 Concentrations: Lessons from Animal Physiology and Earth History." *Journal of Oceanography* 60:705–718.

Precht, W.F. and R.B. Aronson, 2004. "Climate flickers and range shifts of reef corals." *Frontiers in Ecology and the Environment* 2 no. 6:307–314.

Putman, N.F., J.M. Bane, and K.J. Lohmann, 2010. "Sea turtle nesting distributions and oceanographic constraints on hatchling migration." *Proceedings of the Royal Society B: Biological Sciences* 277 no. 1700: 3631–3637.

Rauscher, S. A., F. Giorgi, N. S. Diffenbaugh, and A. Seth, 2008. "Extension and intensification of the Meso-American mid-summer drought in the twenty-first century." *Clim. Dynam.* 31: 551-571.

Rauscher, S. A., F. Kucharski, and D. B. Enfield, 2011. "The role of regional SST warming variations in the drying of Meso-America in future climate projections." *J. Climate* 24:2003-2016.

Reece, J.S., D. Passeri, L. Ehrhart, S.C. Hagen, A. Hays, C. Long, R.F. Noss, M. Bilskie, C. Sanchez, M.V. Schwoerer, and B. Von Holle, 2013. "Sea level rise, land use, and climate change influence the distribution of loggerhead turtle nests at the largest USA rookery (Melbourne Beach, Florida)." *Marine Ecology Progress Series* 493:259-274.

Reich, C.D., R.Z. Poore, and T.D. Hickey, 2013. "The Role of Vermetid Gastropods in the Development of the Florida Middle Ground, Northeast Gulf of Mexico." *Journal of Coastal Research* 63:46–57.

Ropelewski, C.F., and M.S. Halpert. 1986. "North American precipitation and temperature patterns associated with the El Niño/Southern Oscillation (ENSO)." *Mon. Wea. Rev.* 114: 2352-2362.

Rudzin, J.E., S.L. Morey, M.A. Bourassa, S.R. Smith. 2013. "The influence of Loop Current position on winter sea surface temperatures in the Florida Straits." *Earth Interactions* 17: 16, doi:10.1175/2013EI000521.1.

Ruzicka, R.R., M.A. Colella, J.W. Porter, J.M. Morrison, J.A. Kidney, V. Brinkhuis, K.S. Lunz, K.A. Macaulay, L.A. Bartlett, M.K. Meyers, and J. Colee, 2013. "Temporal changes in benthic assemblages on Florida Keys reefs 11 years after the 1997/1998 El Niño." *Marine Ecology Progress Series* 489:125–141.

Schmidt, N., E.K. Lipp, L.B. Rose, and M.E. Luther. 2001. "ENSO influences on seasonal rainfall and river discharge in Florida." *J. Climate*, 14: 615-628.

Shulzitski, K., S. Sponaugle, M. Hauff, K.D. Walter, and R.K. Cowen, 2016. "Encounter with mesoscale eddies enhances survival to settlement in larval coral reef fishes." *Proceedings of the National Academy of Sciences* 113 no. 25:6928–6933.

Smith, S.R., P.M. Green, A.P. Leonardi, and J.J. O'Brien. 1998. "Role of multiple-level tropospheric circulations in forcing ENSO winter precipitation anomalies." *Mon. Wea. Rev*. 126: 3102-3116.

SFRCCC, 2015. "Unified Sea Level Rise Projection for Southeast Florida." Southeast Florida Regional Climate Change Compact Steering Committee. 35 p.

Shamberger, K.E.F., A.L. Cohen, Y. Golbuu, D.C. McCorkle, S.J. Lentz, and H.C. Barkley, 2014. "Diverse coral communities in naturally acidified waters of a western Pacific reef." *Geophysical Research Letters*, 41 no. 2:1–6.

Sponaugle, S., T. Lee, V. Kourafalou, and D. Pinkard, 2005. "Florida Current frontal eddies and the settlement of coral reef fishes." *Limnology and Oceanography*, 50 no. 4:1033–1048.

Stathakopoulos, A. and B.M. Riegl, 2015. "Accretion history of mid-Holocene coral reefs from the southeast Florida continental reef tract, USA." *Coral Reefs*, 34 no. 1:173–187.

Taylor, K. E., R. J. Stouffer, and G. A. Meehl, 2012. "An overview of CMIP5 and the experiment design." *Bull. Amer. Meteor. Soc*., 93:485–498.

Terray, L., L. Corre, S. Cravatte, T. Delcroix, G. Reverdin, and A. Ribes, 2012. "Near-surface salinity as nature's rain gauge to detect human influence on the tropical water cycle." *J. Climate*, 25:958–977.

Todd, A.C., S.L. Morey, and E.P. Chassignet. 2014. "Circulation and cross-shelf transport in the Florida Big Bend." *J. Marine Res.* 72: 445-475.

van Hooidonk, R., J.A. Mayard, Y. Liu, and S.K. Lee., 2015. "Downscaled projections of Caribbean coral bleaching that can inform conservation planning." *Global Change Biology*, 21 no. 9:3389–3401.

Vaz, A.C., C.B. Parins, M.J. Olascoaga, V.H. Kourafalou, H. Kang, and J.K. Reed, 2016. "The perfect storm: Match-mismatch of bio-physical events drives larval reef fish connectivity between Pulley Ridge mesophotic reef and the Florida Keys." *Continental Shelf Research*, 125:136–146.

Walsh, J.J., C.R. Tomas, K.A. Steidinger, J.M. Lenes, F.R. Chen, R.H. Weisberg, L. Zheng, J.H. Landsberg, G.A. Vargo, and C.A. Heil, 2011. "Imprudent fishing harvests and consequent trophic cascades on the West Florida shelf over the last half century: A harbinger of increased human deaths from paralytic shellfish poisoning along the southeastern United States, in response to oligotrophication." *Continental Shelf Research*, 31 no. 9:891–911.

Wang, Z.A., R. Wanninkhof, W.J. Cai, R.H. Byrne, X. Hu, T.H. Peng, and W.J. Huang, 2013. "The marine inorganic carbon system along the Gulf of Mexico and Atlantic coasts of the United States : Insights from a transregional coastal carbon study." *Limnology and Oceanography*, 58 no. 1:325–342.

Wanless H, R.W. Parkinson, and L.P. Tedesco, 1994. "Sea level control on stability of Everglades wetlands." In: Davis SM, Ogdon JC (eds) *Everglades: the ecosystem and its restoration*. St Lucie Press, FL.

Wanninkhof, R., L. Barero, R. Byrne, W.J. Cai, W.J. Huang, J.Z. Zhang, M. Baringer, and C. Langdon, 2015. "Ocean acidification along the Gulf Coast and East Coast of the USA." *Continental Shelf Research*, 98:54–71.

Weil, E. and C.S. Rogers 2011. "Coral Reef Diseases in the Atlantic-Caribbean." In: Z. Dubinsky and N. Stambler (eds.), *Coral Reefs: An Ecosystem in Transition*, Springer Science+Business Media B.V. 201.

Weisberg, R.H., L. Zheng, L.and Y. Liu, Y., 2016. "West Florida shelf upwelling: Origins and pathways." *Journal of Geophysical Research: Oceans*.

Weisberg, R.H, L. Zheng, Y. Liu, C. Lembke, J.M. Lenes, and J.J. 2014. "Why no red tide was observed on the West Florida Continental Shelf in 2010." *Harmful Algae*, 38 no. C:119–126.

Witt, M.J., L.A. Hawkes, M.H. Godfrey, B.J. Godley, and A.C. Broderick, 2010. "Predicting the impacts of climate change on a globally distributed species: the case of the loggerhead turtle." *The Journal of Experimental Biology*, 213:901–911.

Wirt, K.E., P. Hallock, D. Palandro, and K.L. Daly, 2013. "Potential habitat of *Acropora* spp. on Florida reefs." *Applied Geography*, 39:118–127.

Wood, L.D., R. Hardy, P. Meylan, and A. Meylan 2013. "Characterization of a hawksbill turtle (*Eretmochelys imbricata*) foraging aggregation in a high-latitude reef community in southeastern Florida, USA." *Herpetological Conservation and Biology*, 8 no. 1:258–275.

Yates K.K., R.B. Halley, 2006. "Diurnal variation in rates of calcification and carbonate sediment dissolution in Florida Bay." *Estuar Coast* 29 no. 1:24–39.

Yoder, J.A., L.P. Atkinson, S.S. Bishop, E.E. Hofmann, and T.N. Lee, 1983. "Effect of upwelling on phytoplankton productivity of the outer southeastern United States continental shelf." *Continental Shelf Research*, 1 no. 4:385–404.

Zavala-Hidalgo, J., R. Romero-Centeno, A. Mateos-Jasso, S.L. Morey, and B. Martinez-Lopez. 2014. "The response of the Gulf of Mexico to wind and heat flux forcing: What has been learned in recent years?" *Atmosfera* 27, No. 3: 317-334.

Zhang, K., H. Liu, Y. Li, H. Xu, J. Shen, J. Rhome, and T.J. Smith, 2012. "The role of mangroves in attenuating storm surges." *Estuarine, Coastal and Shelf Science*, 102:11–23.