Fishery Ecosystem Plan II
South Atlantic Climate Variability and Fisheries
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1. Executive Summary/Introduction and Role of Climate Considerations in Ecosystem-Based Fisheries Management

Ecosystem-based fisheries management is an approach that takes major ecosystem components and services, both structural and functional, into account in managing fisheries. It values habitat, embraces a multispecies perspective, and is committed to understanding the interconnections of marine life in an ever-changing environment. Its goal is to rebuild and sustain populations, species, biological communities and marine ecosystems at high levels of productivity and biological diversity so as not to jeopardize a wide range of goods and services from marine ecosystems while providing food, revenues and recreation for humans (U.S. National Research Council, 1998)

The ocean and coastal waters of the southeastern United States help drive local weather and regional climate conditions, support ecologically and economically significant ecosystems (which include important fisheries), and provide tourism, boating, and other recreational opportunities. Fish, fishing, and fisheries are major components of the economy, heritage, and ecological systems that support and sustain the unique culture of the southeastern states. In 2014, almost 2.7 million recreational anglers took 17.6 million fishing trips in the South Atlantic region (National Marine Fisheries Service, 2016). In Florida alone, over 2.3 million saltwater anglers contributed $3.9 billion in retail sales (Southwick Associates, 2013). Commercial fisheries in the South Atlantic earned $184 million in landings revenue (NMFS, 2016). These fishing opportunities supported approximately 16 million full- and part-time jobs (NMFS, 2016). Such statistics highlight the economic importance of healthy and sustainable fisheries.

Over the coming decades, climate change is expected to profoundly affect the dynamics of the marine environment across the world. In some regions, and for some attributes, the effect of climate change is expected to be gradual. In others, or for other attributes, the marine environment may change at a much more aggressive pace. This is because the ocean is a dynamic environment that is coupled to global processes at different scales and places. As a testament to this, today many parts of the ocean are already seeing the initial effects of climate change, with the marine environment changing rapidly due to factors such as increased temperature, changes in wind patterns, acidification, decreased dissolved oxygen, and sea level rise (e.g. Doney et al. 2012, Melillo et al. 2014, Nagelkerken and Connell 2015, Nicholls and Cazenave 2010).

Over shorter time scales, climate variability influences marine ecosystems in manners that can exacerbate or ameliorate the effects of long-term climate change. For the purposes of fisheries management, both climate variability (a result of natural variation in the ocean-climate system) and anthropogenic climate change should be considered. Both sources of variability impact the physical and biological conditions that affect the growth, distribution, and mortality of commercial and recreational marine species.

Marine organisms can be sensitive to such changes in their environment, necessitating a greater understanding of current and predicted conditions in the South Atlantic region. Changing conditions are expected to impact everything from migration patterns to life histories to habitat to ecosystem structure. Already, we are beginning to see shifts in species distributions due to climate changes for many species found along the east coast of the United States (Pinsky et al. 2013). These changes highlight the need for the incorporation of climate considerations into a more comprehensive, big-picture approach to management of marine resources through ecosystem-based fisheries management. This approach to management reflects the interconnectedness of ecosystem components and can help managers to ensure a healthy ecosystem and sustainable fisheries in the South Atlantic. Moving forward, climate considerations and associated environmental variability, coupled with a greater understanding of environmental drivers of ecosystem dynamics, will be important to creating more resilient, “climate ready” fisheries.

There is an immediate need to identify and evaluate alternative management strategies under different climate and ocean scenarios to assist managers with choosing the best possible actions for meeting management goals in a changing climate. Today’s management practices may not be the best management practices of the future. Effective fisheries management in a changing climate will require increased coordination and responsiveness of both science and management to changing and perhaps unexpected conditions. Adaptive decision processes that can incorporate, track and respond to climate-related information and as well as the results of management actions will be essential for meeting management goals for fisheries and protected species. Effective production, delivery and use of scientific advice for management decisions can be as important as the management advice itself. Integration of climate science into the management process may necessitate some changes on both the delivery and receiving ends to ensure effective receipt and use of the information. A key step is adoption of climate-smart science and management processes that identify where best to incorporate climate-related information in the management process, use climate-related information to assess risks and best management options, and effectively evaluate and respond to changing conditions (Sobeck, 2015).

This chapter provides a comprehensive and up-to-date review of five related topics: 1) historical and current oceanographic conditions and characterization of the South Atlantic marine environment; 2) predicted future oceanographic conditions; 3) climate impacts on fish, fish habitat and fisheries; 4) knowledge gaps and research priorities related to management needs, and 5) links to South Atlantic Fishery Management Council (SAFMC) management decisions and ecosystem-based fisheries management.

2. Historical and Current Oceanographic Conditions and Characterization

2.1 Atmospheric Drivers

Atmospheric forcing (meteorology) and the Gulf Stream are the two most important forcing factors that control circulation in the South Atlantic. Atmospheric forcing can be described through monthly wind climatology and major episodic events (synoptic fronts and tropical cyclones).

Climatology

The climatology of wind stress on the SAB was systematically examined in the 1980s by Blanton et al. (1985). The seasonal wind patterns found over the area are directly related to the Azores-Bermuda High and the Icelandic Low that form the North Atlantic oscillation (NAO). The monthly climatology over the region is directly related to the position of the region that separates the southward-directed streamlines of the Ohio Valley dry air mass from the northward-directed streamlines of warm and humid air originated from the Azores High.

During spring (March–May) the Azores High contributes to the development of a northward-directed flow of warm humid air mass; it travels westward and turns toward the north over the Gulf of Mexico. This northward air flow intensifies during the summer (June–August) as the Azores High strengthens and shifts westward. During autumn (September–November) the air masses in the SAB are dominated by air masses originating from the Ohio Valley High and produce strong mean southwestward stresses. Details on the movement of these air masses can be found in Wendland and Bryson (1981) and Bryson and Hare (1974).

Weber and Blanton (1980) used wind observations from ships to produce monthly mean wind vectors over the South Atlantic Planning Area. This data set was later updated with ship observations from the Blake Plateau (Blanton et al., 1985), and a more extensive analysis including observations over the period 1945–1963 was produced. Analysis of the International Comprehensive Ocean-Atmosphere Data Set (ICOADS release 2.5 completed in May 2009 with data covering 1662–2007, plus preliminary data and products for 2008 to near-real-time) by Blanton et al., (2003) confirmed the earlier wind climatology described in Weber and Blanton (1980) and Blanton et al. (1985) . Overall five seasonal wind regimes are identified: (i) Winter season (November–February) characterized by a strong southeastward (offshore) directed stress over the northern portion of the SAB, while the winds shift more toward the south in southern latitudes and are of reduced strength. A separation zone (high-pressure ridge) occurs over the Blake Plateau and winds are stronger on the shelf and weaker over the shelf break; (ii) Spring transition (March–May) when the winds gradually shift to eastward and northeastward (poleward) directions in the central portion of the region with more organized winds over the Blake Plateau; (iii) During summer (June–July) winds are westward and southwestward along the southern half of Florida, while the wind stress is more northward and northeastward in the northern half of the region and over the Blake Plateau. Stronger winds are found in July over the northern area and the Blake Plateau with winds largely upwelling favorable, being along-shelf and poleward directed along the entire eastern US coast. Later on in August, a transition regime is developing (Weber and Blanton, 1980) and as the re-analysis of Blanton et al. (2003), using the COADS data, showed weak winds begin to develop and shift counterclockwise from the along-shelf poleward upwelling-favorable summer regime toward the alongshore and south-directed downwelling-favorable direction; (iv) Finally during autumn (September –October) strong southwestward along-shelf wind stresses develop which do not extend all the way to the Blake Plateau; there the mean stress is smaller and mostly westward.

Synoptic fronts & Tropical Cyclones (Hurricanes)

Synoptic variations in meteorological forcing over the SAB are the result of the passage of low-pressure atmospheric frontal systems that are characterized as 1) cold fronts, 2) warm fronts, and 3) extratropical storms. Low-pressure systems associated with cold fronts move from west to east-northeast, and change the wind direction from northeast to southwest. Conversely, warm fronts are accompanied by an opposite change in wind direction. Extratropical storms moving nearshore rotate the wind direction slowly from southwest to southeast. Each storm system has a characteristic pattern of atmospheric pressure, air temperature and wind velocity. Analysis of meteorological records off South Carolina (Wu et al, in review) has shown that cold and warm fronts last on average 3.5 to 4 days while extratropical disturbances have an average duration of less than 2 days. The same analysis has shown that their frequency of occurrence is on average 30 cold fronts, 20 warm fronts, and 16 extratropical disturbances per year. These are typical for the region and can be found from North Carolina to Florida and contribute to mixing of the shelf waters and development of subtidal circulation over the shelf.

In addition to the synoptic fronts, the southeast US in general is subject to the influence of tropical cyclones. Their climatology for the Atlantic region is maintained and continuously updated by the National Weather Service (NWS) National Hurricane Center in Miami, Florida. Overall, the Atlantic (including the Atlantic Ocean, Caribbean Sea, and Gulf of Mexico) hurricane season starts 1 June and extends to 30 November and the peak season is mid-September. Mann and Emanuel (2006) have suggested a positive correlation between sea surface temperatures and Atlantic basin tropical cyclones while Holland and Webster (2007) have found a doubling of the number of tropical cyclones over the past 100 years. These studies suggest that these increases are due to human-driven greenhouse warming. However, Landsea (2007) has argued that such conclusions are due solely to bias in the data set imposed by the improved monitoring systems that have been in place in recent years. In particular, Landsea et al. (2010) noted that the increase of recorded short-lived storms (duration up to two days) has led to the previously stated conclusions about the increased frequency of tropical storms.

2.2 Oceanographic Drivers

The presence of the warm Gulf Stream flowing northeast along the offshore edge of the outer shelf and continental break is a dominant oceanographic feature in the region. The warm waters of the current create a geographically narrow corridor of habitat suitable for tropical and subtropical species, particularly in demersal habitats where the wintertime cooling associated with low atmospheric temperatures is confined to the surface layers of the ocean. Ocean temperatures are more seasonably variable in shallower waters of the middle and inner shelf between the Gulf stream and the coast, particularly north of Florida. Waters of this region are warm in summer, and the horizontal temperature gradient between the coast and the outer shelf is small. In contrast, waters of the inner and middle shelf are reduced significantly in winter, and mixing of the water column leads to cool, temperate ocean conditions in shallower waters. Temperatures, particularly along the seafloor, increase from the inner shelf to the shelf break during winter. Further, interannual temperature variation on the inner shelf is greater during winter than in summer. An exception to this pattern is coastal Florida where interannual temperature variation is similar in winter and summer, which may reflect variable summer upwelling events. Overall, the seasonal climatology described above is modified by eddies and meanders of the Gulf Stream at weekly to monthly time scales.

The distribution of salinities in the South Atlantic Bight exhibits seasonal variation. During summer, surface and bottom salinity is relatively homogenous throughout the continental shelf region. However, during other seasons there is a cross-shelf gradient and lower salinities are found in shallower areas. Lowest salinities are observed in late-spring coincident with high river discharge, particularly on the inner shelf off South Carolina and Georgia.

The presence of the Gulf Stream also has a significant influence on the density stratification of the region. Waters of the shelf break are permanently stratified, with maximum stratification in summer. In shallower waters, rapid cooling in fall decreases stratification, and the water column is relatively well-mixed between November and March (Blanton et al., 2003). Stratification of shelf waters increases with the peak of freshwater discharge from local rivers in March and April (Atkinson et al., 1983). By July, stratification is strong throughout the shelf (Blanton et al., 2003).

Interannual variability in the hydrographic properties remains poorly characterized but is likely sensitive to variability in the seasonality of freshwater flux from rivers, surface heat flux, and position of the Gulf Stream.

The influences of the Gulf Stream are of particular importance because they provide an efficient avenue for the transport of nutrients, heat, and marine organisms between the sub-regions of the coastal southeast US, but also contribute significantly to cross-shore fluxes of momentum, heat flux, and nutrients.

Lee et al., (1991) described the two modes of Gulf Stream variability. The first signature is associated with mean onshore fluxes of nitrate off GA and NC, and it is related to Gulf Stream meander variability in the 3-20 day band. Meanders upwell deep cold nutrient-rich waters onto the outer SAB shelf, which subsequently can be advected onto the mid-shelf, under summertime stratification and upwelling favorable wind conditions. Regions of meander decay correspond to regions of net nutrient import, providing a large annual nutrient source for new production on the SAB shelf (Lee et al., 1991). Individual meander-forced upwelled intrusions on the Georgia shelf have been mapped, and volumes of water imported can exceed 35 km^3 (Paffenhofer et al., 1987). Summer intrusions have been tracked and mapped for periods of several weeks, although their frequency, variation in spatial extent, lifetimes on the shelf and ultimate export pathways are not explicitly defined. In winter, lack of vertical stratification and absence of upwelling favorable wind suppresses shoreward spreading of meander induced fluxes at the shelf break (Castelao, 2011), so while Gulf Stream meander variability is relatively independent of season, the extent to which meander intrusions promote subsurface fall and winter new production is not well quantified.

The second signature of Gulf Stream variability shown in Lee et al., (1991) is the cyclonic ‘Charleston Gyre’ found between the shelf edge and the offshore-deflected Gulf Stream off Long Bay. This feature is associated with local bathymetric features and its presence is related to documented shifts in the Gulf Stream position off Long Bay. In this location, the GS occupies one of two preferred (weakly and strongly) deflection states (Bane and Dewar, 1988; Lee et al., 1991, Savidge et al., 1992), for several weeks at a time, and abruptly switches from one state to the other. Gulf Stream position affects shelf circulation on the mid-shelf and outer shelf. Savidge et al., (1992) demonstrated that larger offshore displacement of the Gulf Stream is associated with reduced northward shelf flow in Long Bay.

Over the SAB, along-shelf flow is primarily wind forced, especially on the inner and mid-shelf (Lee et al., 1991). In general, shelf circulation follows the prevailing wind forcing (northward in spring and summer, southward in fall, and predominantly southeastward in winter, see Weber and Blanton 1980; Blanton et al., 2003). These general patterns are modulated by the short (3-5 days) synoptic fronts described earlier (warm, cold and extratropical fronts). Seaward of the 40m isobath to the shelf break, shelf circulation also responds strongly to the adjacent GS (poleward flows), whose edge follows the shelf break along the SAB shelf except off Long Bay. In there the Charleston Gyre often modifies wind-driven circulation driving southward directed flows.

2.3 Hydrologic drivers

The Southeast has a humid climate with an abundance of precipitation. Recent studies (e.g., Labosier and Quiring, 2013) however, suggest that the region is characterized by significant precipitation variability marked by heavy, intense precipitation, interspersed with dry periods. Consequently, both floods and droughts may become more common in the future. The relationship between climate indices and hydrological cycle in the southeast is being established. Generally speaking, warm El Niño phases lead to positive precipitation anomalies in much of the region, while cold La Niña phases result in negative precipitation anomalies. Less well-studied are other established oceanic–atmospheric indices, including the Pacific Decadal Oscillation, and the Arctic Oscillation. Despite their destructive potential, tropical cyclones (TC) contribute heavily to the Southeast’s annual precipitation and are fundamental to the region’s hydroclimatology. TC-induced precipitation plays a significant role in the spatial and temporal patterns of water resources throughout the region, especially in coastal and nearcoastal areas. TC-precipitation accounts for a significant proportion of precipitation in many locations in the Southeast, and a lack of it can lead to serious soil moisture deficits and droughts. Likewise, TCs have the potential to alleviate drought conditions. Increasing trends in TC-induced precipitation are present throughout parts of the region.

More investigation of precipitation variability on intrannual and interannual timescales is necessary. While year to year variability and total annual precipitation may remain constant, variability may shift within years leading to significant management and planning implications. It is also not well understood what factors drive the recent variability seen in the region. Future studies will need to decipher natural versus anthropogenic drivers, as well the degree to which each influences hydroclimate variability. Furthermore, downscaling of climate model output will be necessary to make climate projections more useful for the water resource manager. Alongside future hydroclimatic change are also changes in land use/land change and population growth that will also contribute to the already complex hydroclimatology of the Southeast.

Nutrients

Excess nitrogen and phosphorus loading impacts not only local waters, but also downstream waterbodies and coastal systems. The USGS National Water-Quality Assessment (NAWQA) program assessed total nitrogen and total phosphorus yields in over 8,000 stream reaches throughout the southeastern United States using the USGS watershed model SPARROW (Spatially Referenced Regression On Watershed Attributes). The southeast regional SPARROW model integrates Federal, State, and local agency monitoring data at over 300 stations with geospatial data describing nutrient inputs from fertilizer or agricultural land use, animal waste, urban land use, atmospheric deposition (nitrogen only), weathering or mining of rock (phosphorus only), and wastewater discharges, as well as physical characteristics of the watershed properties such as soil properties and precipitation).

Results from the southeast regional models can be used to assess:

- transport of nitrogen and phosphorus to streams from watersheds,
- removal of nitrogen by processes within streams,
- contributions of nitrogen and phosphorus from different sources in watersheds,
- transport and delivery of nitrogen and phosphorus to receiving water bodies, including the 16 major estuaries along the South Atlantic and Gulf Coasts,
- conditions and transport in unmonitored streams,
- priorities for future monitoring and assessment, and
- response of nutrient levels to proposed management actions.

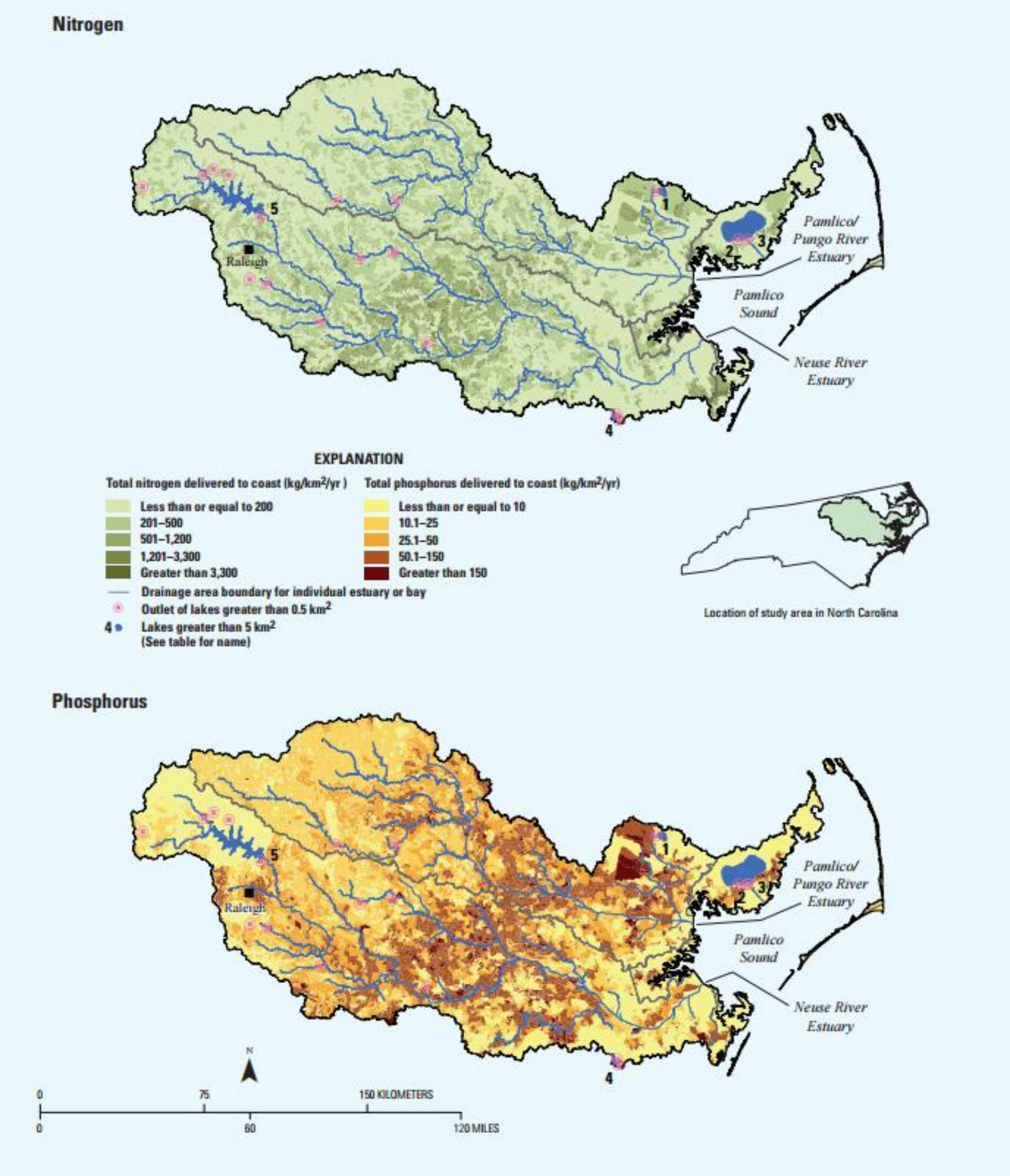
Estimated statewide total nitrogen (TN) and total phosphorus (TP) loads and yields, as predicted by the regional USGS SPARROW models.

State	Net incremental TN load (1000 kg/yr)	Average TN yield (kg/yr/km^2)	Net incremental TP load (1000 kg/yr)	Average TP yield (kg/yr/km^2)
Florida	37,286	359	7,465	72

Georgia	60,007	396	6,168	41
North Carolina	59,194	465	6,493	51
South Carolina	28,173	355	3,049	38

Major sources of nitrogen and phosphorus delivered to the coast often occur far up into the watershed. Large agricultural areas and major cities in the coastal plain and piedmont ecoregions typically contribute the most nutrients to the coast (Moorman et al., 2014)

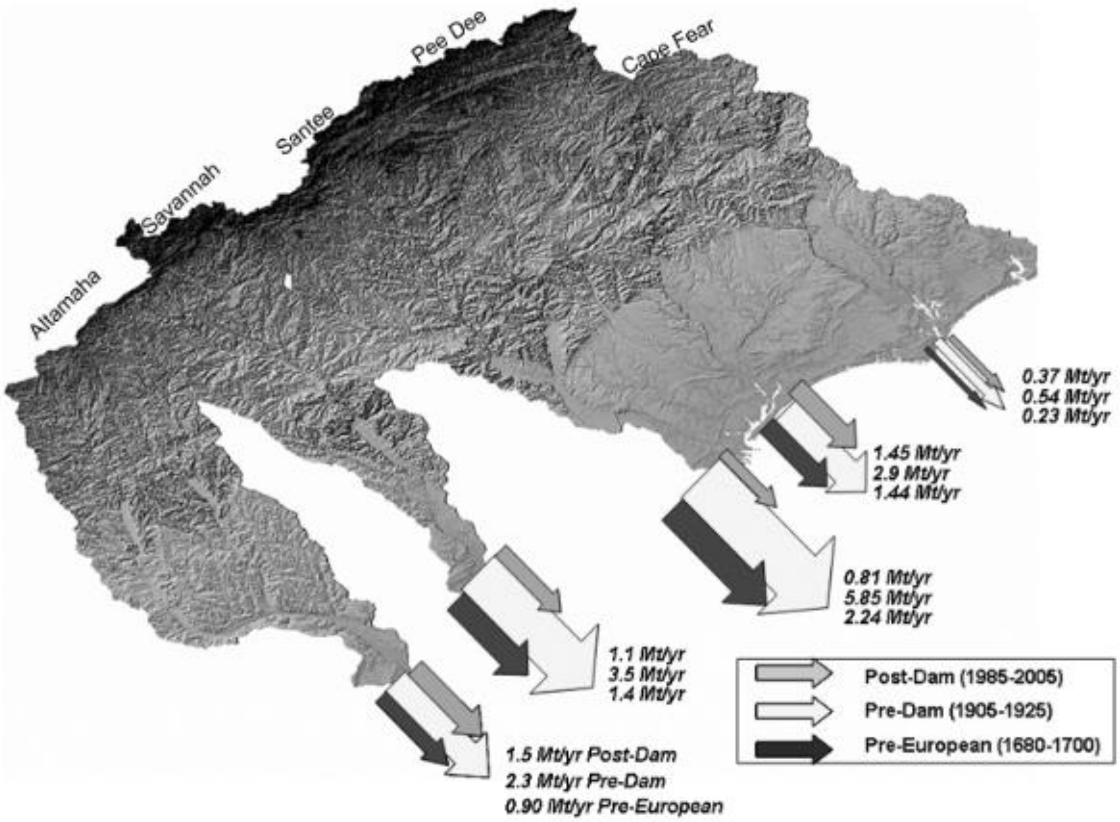
Contributing watersheds and nutrient yield for Pamlico Sound and Pamlico/Pungo and Neuse River Estuaries based on USGS SPARROW models (Moorman et al., 2014).



Sediment

Sources and amount of suspended sediment delivered to the South Atlantic Bight from major rivers has changed significantly since pre-European settlement (McCarney-Castle et al. 2010). The arrival of European settlers, and subsequent deforestation greatly increased sediment delivery through most of the 1900s. Starting in the 1970s, the large-scale creations of dams and reservoirs in the region drastically reduced sediment delivery to levels close to pre-european levels (McCarney-Castle et al. 2010).

Climate changes over the last 300 years appear to have had very little impact of sediment delivery and most changes seem to be driven by anthropogenic decisions (McCarney-Castle et al. 2010). It is difficult to predict future changes in sediment loads. While sediment loads may increase due to ongoing removal of dams from fish passage and restoration efforts, they may also decrease as increasing water demand from rapidly growing urban communities in the Piedmont leads to construction of new reservoirs.



Predicted historic and modern sediment load into the South Atlantic Bight from 5 major river basins (McCarney-Castle et al. 2010)

- History (Past sources, particularly previous land clearing for farming)
- Hydrologic alterations limiting sediment movement
- Current trends in decreasing sediment loads

2.4 Lower-trophic-level ecosystem properties

Analyses of remotely-sensed ocean color in shelf waters of the South Atlantic Bight indicate that chlorophyll concentrations exhibit a high level of seasonal variability, with a strong, inverse correlation with surface temperatures. Chlorophyll concentrations are greatest during cool months of the year (November through March) and lowest during summer months due to stratification of the water column, which leads to nutrient limitation (Barnard et al., 1997; Miles and He, 2010). Chlorophyll concentrations are also generally higher on the inner continental shelf and vary regionally. For example, greater and more variable rates of primary production are present on the Florida continental shelf due to the influence of upwelling events in this area (Miles and He, 2010). Seasonal variability and correlations with ocean temperatures are reduced near the shelf break, where the presence of the Gulf Stream minimizes the seasonal cycle in temperature, mixing, and nutrient supply.

3. Predicted Future Oceanographic Conditions

In coming decades, surface air temperatures are expected to increase as a result of anthropogenic emissions of greenhouse gases. Ocean temperatures are also expected to warm, with a general poleward movement of isotherms. However, future temperature changes in the South Atlantic Bight are expected to differ slightly from this global mean. While the basin-scale orientation of temperature gradients are in the meridional direction, gradients in the South Atlantic Bight generally follow bathymetric contours and are a function of the offshore location of the warm Gulf Stream and the wintertime cooling of waters on the inner and middle shelf. Future warming is expected to result in a shift of warm isotherms toward the coast, particularly in winter when the gradient in water temperature is the steepest (Grieve et al., 2016).

Changes in the seasonal timing of density stratification over the continental shelf of the South Atlantic Bight is expected to be sensitive to changes in surface heat flux and seasonal winds. Over scales relevant to anthropogenic climate change, density stratification of shelf waters is expected to occur earlier in the year. As a consequence, the period of low chlorophyll concentration that is associated with nutrient limitation in summer is also expected to occur earlier in the year and persist later in the fall.

3.1 Ocean Chemistry

Given the continuing increase in atmospheric concentrations of carbon dioxide, the future oceans will be characterized by reductions in the carbonate and aragonite saturation states and pH. Since pre-industrial times, surface ocean pH has declined about 0.1 pH units, equivalent to a 30% increase in the concentration of hydrogen ions (Feely et al., 2009). These changes in the mean state of the ocean carbon chemistry are well understood, and decreases in carbonate saturation state have been shown to negatively impact the formation and maintenance of aragonite and calcium carbonate shells (Feely et al., 2008). However, impacts of ocean acidification on marine populations and ecosystems remain an area of active research. Shallow, highly productive environments are naturally subject to a high degree of variability in the carbon concentrations at a variety of time scales, a result of diurnal and seasonal variability in primary production (and the consequent changes in CO2 flux). Organisms in these environments have adapted to such variability, and their susceptibility to anthropogenic ocean acidification remains uncertain.

Increases in ocean temperatures and decreases in ventilation (i.e., reduced mixing resulting from increased density stratification) acts to reduce dissolved oxygen content of surface and subsurface waters. In coastal estuaries where increasing supply of both organic and inorganic nutrients may be associated with coastal development, increases in microbial respiration may also lead to decreased concentrations of dissolved oxygen and development of hypoxia, even in ecosystems that are relatively well vertically mixed (Verity et al., 2006). Additionally, shelf waters may be subject to episodic intrusions of waters with low dissolved oxygen concentrations that are associated with upwelling forced by southwesterly winds. Project long-term changes in this process remains to be quantified (Sanger et al., 2012).

In January 2016, the Southeast Ocean and Coastal Acidification Network held a workshop to discuss the state of ocean acidification science, prioritizations and vulnerabilities of the region (Wickes 2016). The meeting sought to accomplish three objectives: 1) summarize key findings, prioritize research needs, and identify research and laboratory capabilities that could address ocean and coastal acidification research questions; 2) identify why the Southeast region is unique and its vulnerabilities to potential impacts of ocean acidification; and 3) summarize why ocean acidification matters to stakeholders. Some of the key conclusions from the meeting included:

- Ocean and coastal acidification is driven by local and regional processes such as eutrophication, upwelling, and freshwater flow to the coast, as well as by global ocean uptake of carbon dioxide (CO2) that is increasing in the atmosphere due to the burning of fossil fuels, land use change, and cement production.
- Ocean acidification affects all marine waters, and has been shown in laboratory experiments to negatively impact those marine species that grow by producing shells of calcium carbonate minerals such as oysters, clams, mussels, and corals
- The Southeast region is unique from other U.S. coastal regions because it spans subtropical to tropical climate zones, and displays unique and extreme environmental conditions, stressors and gradients.

- Many species in the Southeast are adapted to highly variable estuarine conditions, including wide fluctuations in pH, but how this affects their vulnerability to ocean and coastal acidification is unknown.
- Shellfisheries and coral reefs, which are important to the culture and the economy of the Southeast region, are particularly vulnerable because acidification can directly impair the growth of species with carbonate shells and skeletons. A number of shellfish hatcheries have experienced significant die-offs, although the cause is not currently known.
- We have a good base of information to help build our knowledge on impacts to the Southeast, and ways to prepare society to manage the consequences.

3.2 Sea Level Rise

Sea level rise has been documented by diverse geophysical studies in the southeast U.S., with regional variation identified in rates and societal vulnerability (e.g., Kemp et al. 2009; Tebaldi et al. 2012). Most areas in the southeast U.S. region are projected to experience an approximately 0.75-1m rise in sea level by 2100 (Kopp et al. 2014, Parris et al. 2012), but this will differ on local scales. For example, Parkinson et al. (2015) examined rates of current and predicted rise for seven regions throughout Florida. On the east coast of Florida, the region of highest vulnerability consists of Palm Beach, Broward, Miami-Dade, and Monroe with increases that will range from 5-20 mm/yr. These rates of sea level rise will result in coastal flooding, seawater intrusion, and loss of estuaries and coastal wetlands. Important habitats such as salt marshes, shoals, mud flats, and mangrove forests may be lost (Glick and Clough 2006). These impacts may negatively impact estuarine species less tolerant of salinity changes and lead to changes in estuarine productivity (National Marine Fisheries Service, 2017).

Sea level rise will also have impacts in terms of socio-economic changes (e.g., levels of habitation of the Florida Keys and Dade County by 2100), losses of or transitions in coastal waterfronts (including seafood off-loading and processing areas), and other factors that could emerge in coming decades. However, many policy responses to sea level rise involve complex socio-economic and communication challenges and are explicitly unaddressed in coastal Florida and North Carolina (Lindeman et al. 2015).

3.3. Temperature, precipitation and hydrology

U.S. National Climate Assessment (Melillo, et al., 2014) reports that temperatures across the Southeast and Caribbean are expected to increase during this century, with shorter-term (year-to-year and decade-to-decade) fluctuations over time due to natural climate variability. Major consequences of warming include significant increases in the number of hot days (95°F or above) and decreases in freezing events. Although projected increases for some parts of the region by the year 2100 are generally smaller than for other regions of the United States, projected increases for interior states of the region are larger than coastal regions by 1°F to 2°F. Regional average increases are in the range of 4°F to 8°F (combined 25th to 75th percentile range for A2 and B1 emissions scenarios).

Projections of future precipitation patterns are less certain than projections for temperature increases. Because the Southeast is located in the transition zone between projected wetter conditions to the north and drier conditions to the southwest, many of the model projections show only small changes relative to natural variations. However, many models do project drier conditions in the far southwest of the region and wetter conditions in the far northeast of the region, consistent with the larger continental-scale pattern of wetness and dryness. In general, annual average decreases are likely to be spread across the entire region. Projections further suggest that warming will cause tropical storms to be fewer in number globally, but stronger in force, with more Category 4 and 5 storms. On top of the large increases in extreme precipitation observed during last century and early this century, substantial further increases are projected as this century progresses.

4. Climate Impacts on Fish, Fish Habitat and Fisheries

4.1 Abundance and Distribution

Climate variability plays a major role in the abundance and availability of fishery resources each year (Hare et al. 2016). The influence of climate can be observed at multiple temporal scales. Interannual variation (e.g., cold vs. warm year) can drive the abundance of short-lived species, including many valuable forage species like anchovy, squid and shrimp. For example, white and pink shrimp are vulnerable to winter kills, and closures may be enacted to protect the spawning stock of these species in the southeast (Shrimp FMP, Amendment 9). Commercial catches of other fisheries in the southeast, such as Spanish mackerel and bluefish, have also been related to interannual variability in temperature (Morley et al. 2016).

Climate change, however, operates on a larger scale and can influence fisheries in multiple ways. Temperature sets boundaries on the geographic ranges of marine species (Sunday et al. 2012). For any given species, climate change may lead to a spatial shift in the location of suitable temperatures, which in turn changes the distribution of habitat (Pinsky et al. 2013). Mobile-pelagic species often respond rapidly to shifts in preferred thermal habitat because of the directed movement of individuals, while responses of benthic species may be more complex (Sunday et al. 2015). For example, suitable habitat for species within the snapper-grouper complex off the southeast U.S. occurs where preferred temperatures and benthic attributes overlap (Bacheler and Ballenger 2015). Therefore, distribution shifts of these species will depend on the availability of suitable structured habitat as preferred temperatures expand into new areas.

Increased temperatures can also change the seasonal availability of migratory species or can affect the productivity of a stock in a given region. For example, in 2015 and 2016 the recreational landings for cobia (NY to GA) and blueline tilefish significantly exceeded the annual catch limits (NMFS Southeast Regional Office, 2017). These years coincided with unexpected high catches in the mid-Atlantic region, so cobia and blueline tilefish may be responding to increasing temperatures in the northeast. However, these issues remain unresolved and indicate a strong need to examine how climate change may influence traditional stock boundaries of fishery resources in the southeast.

4.2 Thermal Envelopes

A vast majority of species targeted by fisheries are ectothermic, which means their body temperature conforms to the surrounding water temperature. All metabolic processes (e.g., protein synthesis and growth, swimming speed, etc.) are highly dependent on temperature. Every species is adapted to perform well within a specific range of temperatures, which is described as the thermal envelope of a species (Pörtner and Knust 2007). At temperatures beyond (either above or below) the thermal envelope, individuals become increasingly limited in their ability to maintain basic metabolic processes (Pörtner 2002). For example, the ventilation (i.e., gills) and circulatory systems supply oxygen to the body, and these systems have an optimal performance temperature. As temperatures increase beyond this level, oxygen supply declines, despite continued increases in basic metabolic needs. This results in a reduced growth potential and scope for activity at temperatures outside of the thermal envelope. Extreme temperatures are typically lethal due to a breakdown of cellular functioning.

One concern is that the rate of climate change will exceed the rate of adaptive change to changing environmental conditions. If this occurs, the options available to marine species to mediate the impacts of climate change are limited. They can respond in two major ways: exhibit spatial distribution shifts and/or phenology changes. Both responses reflect the species attempt to cope with changing environmental conditions.

Spatial distribution changes result from a species tracking its thermal envelope as it shifts across the seascape, which can result in latitudinal shifts or changes in depth (Pinsky et al. 2013). Northward shifts and/or expansions of species ranges have been documented in the South Atlantic for species such as cobia and white shrimp (Pinsky et al. 2013) and in the northern Gulf of Mexico for species such as red grouper and yellowtail snapper (Fodrie et al. 2010). The mechanisms behind such shifts depend on species motility (e.g., coastal-migratory vs. reef oriented vs. sedentary), reproductive strategy (e.g., wide larval dispersal vs. locally retained larvae), and juvenile thermal tolerance in some species. For example, the adult range of gray snapper in the southeast U.S. is largely limited by the overwinter survival of juveniles which may change geographically with the warming of waters in current northern boundaries (Wuenschel et al., 2012). In regions of rapid temperature change, such as the northeast U.S., species can respond rapidly. For example, distributions of scup and black sea bass in the Mid-Atlantic Bight have shifted northward by 150-200 km in the past four decades (Bell et al. 2015). Unfortunately, species exhibiting low motility (e.g., corals, attached bivalves, etc.) and limited larval dispersal (e.g. oyster toadfish, seahorses, etc.) have a limited scope to account for climate change with species distributional shifts. A similar distributional shift may occur in the face of changing ocean acidification, which we expect to occur in a warmer ocean (Calosi et al. 2017).

4.3 Phenology

Shifts in species phenology, which refers to the annual timing of life history events (e.g., timing of reproductive period, timing of migrations, etc.), result from species attempting to account for changes in the average environmental conditions experienced by individuals in a population. For example, species may shift their reproductive season as environmental conditions, particularly temperature, is critical for successful reproduction, as early life stages have specific and narrow requirements for survival (Rijnsdorp et al. 2009). Reproductive strategies evolve to maximize the probability that offspring will experience favorable environmental conditions, and thus maximize the probability that their young survive to reproduce. By doing so, the fitness of individuals will be maximized. Climate change can affect both the timing of reproduction and the spatial extent of suitable spawning habitat. Unless there is enough plasticity in the reproductive strategy of the species to account for such shifts, the reproductive potential of the population will ultimately be affected. Another potential shift in phenology may occur with regards to the annual timing of migration (either across shelf or alongshore) for migratory species (Mills et al. 2013, Morley et al. 2016, Sims et al. 2001). Such migrations evolved to facilitate the presence of individuals of that species being in particular areas (e.g. for feeding or reproduction) at certain times of the year. Timing of migrations are often cued via environmental conditions (e.g. temperature), so climate variability can impact the seasonal availability of fishery resources in particular areas (Mills et al. 2013) and affect the “growth potential” of the population by altering mortality rates (e.g. higher mortality because mistimed presence on appropriate foraging grounds) and/or reproductive potential (e.g. not on spawning grounds when chances of survival are maximized).

4.4 Spawning, Dispersal, and Connectivity

For many South Atlantic species, particularly sessile invertebrates and benthic fishes, dispersal during the pelagic larval stage is a key feature of the life cycle. Larval transport provides demographic connectivity that links distant portions of the habitat. This connectivity can provide resilience against local disturbances, and is critical to understanding population persistence (reviewed by Botsford et al. 2009, Cowen and Sponaugle 2009). Larval dispersal distances are shaped by a complex interaction of ecological factors: the timing of spawning, larval development time, ocean circulation, larval behavior (e.g., vertical migration, navigation), and the planktonic food supply available to larvae. Many of these factors are likely to shift in the face of a changing and increasingly variable climate. For example, temperature affects metabolism rates and is a major driver of gonadal development and spawning (Lowerre-Barbieri et al. 2011), and therefore climate-induced changes in temperature regimes can be expected to influence spawning times and locations. Indeed, changes in temperature have been linked to alterations in spawning times for a number of marine fish species such as North Sea mackerel (Jansen and Gislason 2011), flounder (Sims et al. 2005), cod (Wieland et al. 2000) and Bluefin tuna (Muhling et al. 2011). As the phenology of both spawning activity and primary productivity shifts, this may lead to mismatches between the time larvae are in the water and the availability of their prey (Durant et al 2007, Edwards and Richardson 2004) causing starvation and high mortality, and lower energetic reserves in surviving larvae (McLeod et al. 2013, Kristiansen et al. 2014).

Because fish and invertebrate larvae are ectothermic, we generally expect larval durations to shorten and larval growth to speed up. This leads to the general expectation that overall dispersal distances will shorten, reducing connectivity (O’Connor et al. 2007, Munday et al. 2009). However, experimental results (most of which have been conducted with tropical fishes) do not always follow this pattern; if warming exceeds the thermal optima for fish development then larval durations may actually lengthen in warm conditions (McLeod et al. 2013). Additionally, the temperature-dependent acceleration in larval development also increases larval food requirements: a combination of high temperatures and low food availability can further lengthen larval durations (McLeod et al. 2013). The effects of reduced planktonic productivity are of particular concern in the South Atlantic Bight due to expectations that increased stratification will lead to earlier, longer periods of low summertime chlorophyll (see Future Ocean Conditions). Ocean acidification is also likely to affect connectivity, both via impairments to navigation and habitat selection by late-stage larvae (Munday et al. 2010) and by imposing additional physiological costs on larvae that impair development and increase mortality (Munday et al 2009).

Climate change and variability will affect multiple processes associated with larval dispersal and connectivity simultaneously, and in possibly different directions. For example, increasing temperatures and shifts in prey availability may either shorten or lengthen development times, and changes in ocean circulation may either hasten or slow current velocities, depending on location and season. These complex interactions make it difficult to draw general conclusions regarding likely shifts in connectivity. Instead, such predictions require site-specific modeling of both oceanography and larval behavior to quantify the relative contribution of each process. Such work has been completed for other regions but not the South Atlantic (e.g., Lett et al. 2010, Aiken et al. 2011, Andrello et al. 2015). However, we can make the general prediction that increased variability in larval survival will lead to net decreases in population density. This is because the recruitment of most species is governed by a nonlinear, density-dependent stock-recruit relationship that reflects competition for resources (food, predator refuges, etc.) among new recruits. As a consequence, the magnitude of positive fluctuations in larval survival (‘good years’) are damped by density-dependent competition, while the magnitude of negative fluctuations (‘bad years’) is not. Thus good years cannot balance out bad years, and the net effect of increasing variability is reduced mean recruitment over the long term (Armsworth 2002).

Many species in the region undergo ontogenetic migrations, sometimes recruiting as larvae to upper estuaries then migrating to the lower estuary and finally offshore as adults (Able and Fahay 2010). This movement is another form of spatial connectivity that is essential to the understanding of population dynamics in these species (St. Mary et al. 2010, Grüss et al. 2011, White 2015). However, there are few specific predictions of the effects of climate variability on ontogenetic migrations. In general the life stage most vulnerable to variable conditions is the larvae and early juveniles; these stages will also be found in the upper estuary where they are vulnerable to both high temperatures and increasingly frequent hypoxic conditions.

4.5 Trophic Interactions

Climate change may alter foodweb dynamics and trophic structure throughout the region. Alterations in primary and secondary production may lead to changes that cascade through the food web and have a direct impact on fish and fisheries (Brander 2010). The physiology and behavior of organisms is changing and impacting size structure, spatial distribution, and seasonal abundance of both prey and predators which may lead to altered species interactions affecting a range of organisms from phytoplankton to marine mammals (Doney et al. 2012). For example, warming ocean temperatures can lead to increased consumption rates and stronger top-down effects (Sanford 1999, Philippart et al. 2003). Ocean acidification can negatively impact important prey species which depend on calcium metabolism, such as diatoms, shellfish, and both soft and hard corals (Doney et al. 2012). Changing environmental conditions can lead to asynchronous shifts in seasonal phenologies of predator and prey populations (i.e. match-mismatch hypothesis) and disrupt existing trophic interactions (Doney et al. 2012). As scientists and managers seek to better understand the impacts of climate change on marine ecosystems, it will be important to look at these community level impacts. For additional information see the Food Webs and Connectivity chapter of the Fishery Ecosystem Plan.

4.6 Disease and parasites

Increasing water temperatures have been linked to increases in the prevalence and distribution of marine disease outbreaks (Harvell et al. 2009). This is likely due to the expansion of pathogen ranges as temperatures warm and increased susceptibility by the host due to environmental stress. The severity of disease is also expected to increase as pathogens are generally favored by warmer temperatures relative to their hosts (Harvell et al. 2002). For example, warming in the early 1990s led to the spread of the oyster parasite, *Perkinsus marinus*, across a 500 km range and caused mass fatalities in the oyster's populations. Research shows that increased temperatures are also associated with increased frequency of disease and bleaching events in reef-building corals (Bruno et al. 2007).

4.7 Invasive Species

The climatology of the South Atlantic Bight is a major factor shaping the distribution and abundance of invasive species in this region. Lionfish (*Pterois volitans*, *P. miles*) have received much attention because they threaten fisheries associated with the structured habitats on the continental shelf. The distribution of adult lionfish is restricted to areas where winter temperatures remain above 15°C (Whitfield et al. 2014), because low temperatures cause cold stress and mortality (Kimball et al. 2004). This prevents adult lionfish from occupying depths below 27 m north of Florida (Whitfield et al. 2014). However, in structured habitats of the outer continental shelf lionfish are a dominant species and can outnumber most targeted fishery species including groupers and porgies (Whitfield et al. 2007, 2014). The predatory impact of lionfish at high densities is large (Cerino et al. 2013), and they have similar feeding habits as economically important species like scamp grouper (Munoz et al. 2011). However, lionfish impacts on the productivity of important fisheries remains poorly understood. In their native range lionfish occupy shallower habitats, so increasing temperatures in the southeast region may lead to an expansion of suitable habitat into shallower areas. Evidence for this prediction comes from an earlier warming period off North Carolina before lionfish were established. Parker and Dixon (1998) found that a region of North Carolina's continental shelf, known as 210 rock, experienced an increase in the number of tropical species following a period of increased winter-water temperatures during the 1980s. It is noteworthy that multiple tropical-Pacific fish species, in addition to lionfish, have been observed off Florida (Semmens et al. 2004).

In estuarine habitats, interannual variability in winter temperatures may limit the northward expansion of potentially invasive tropical species from south Florida and the Caribbean

(Canning-Clode et al. 2011). Some of these species are native to tropical regions, but have the potential to thrive off the southeast coast. One example is the green porcelain crab (*Petrolisthes armatus*), which is widespread in the tropical Atlantic occupying structured coastal habitats (see Hollebone and Hay 2007). It is an emerging invasive species of the southeast U.S. where it occupies oyster reefs and is capable of outnumbering native crab species and also reaching densities that are far greater than what is reported in its natural range (Hollebone and Hay 2007). However, the permanent establishment of this species north of Florida appears to be limited by periodic cold events during winter (Canning-Clode et al. 2011). Climate variability may also play a key role in limiting the northward spread of invasive species that are established in the tropical Atlantic. For example, Asian tiger shrimp are a widespread invasive that may already be established in the South Atlantic Bight (Fuller et al. 2014). However, to predict the impact of this species in the region, a better understanding of how temperature variability interacts with reproduction and life history is needed.

4.8 Age-structure Truncation and Sensitivity to Climate Variability

Aside from reducing overall abundance, size-selective harvest has the additional effect of truncating the population age distribution. As older ages become less abundant, reproduction is compressed into just a few age classes (in the extreme, populations can become effectively semelparous, spawning only once on average before being harvested). The consequence of this truncation is a heightened sensitivity to environmental variability at particular characteristic frequencies. Essentially, if a climatic anomaly produces a strong (or weak) recruit year class, that anomaly will continue to resonate in future years as the cohort matures and reproduces, producing a second anomaly in recruitment. This ‘echo effect’ or ‘cohort resonance’ is amplified as the age structure is truncated, and also if a dominant mode of environmental variability coincides with the generation time (i.e., resonance frequency) of the population (Botsford et al. 2011, 2014). Modes of environmental variability likely to affect populations in the South Atlantic include the North Atlantic Oscillation and the Atlantic Multidecadal Oscillation (e.g., Condron et al. 2005, Hare and Able 2007, Buchheister et al. 2016).

Impacts on People and Fisheries

4.9 Catchability

Climate variability can affect catchability of a species, both in terms of availability to the fishery and vulnerability to gear (e.g. Wall et al. 2009). Changes in availability to the fishery can be a result of changes in the spatial distribution of stocks, as well as the timing of their migrations (Morley et al. 2016). When the preferred physical habitat (e.g., in terms of temperature, oxygen levels, or current regimes) of a fish species is altered, fish can migrate away from traditional fishing grounds to locations that are less accessible to fishers, thereby reducing availability. Changes in timing of migrations may also make stocks less predictable for targeting; for example, warming earlier in the year may force fish to migrate to northern areas sooner and more extensively, making them less available to fishers in some areas while simultaneously increasing availability in other areas. These affects can produce increases or reductions in landings and catch rates that are not proportional to actual changes in the stock biomass. Catch rates can also be increased or decreased due to changes in vulnerability (Stramma et al. 2012). For example, if surface waters increase in temperature and fish distribute deeper in the water column, then some surface gears may become ineffective in catching the fish. Some fishers will respond by adapting and making use of subsurface fishing techniques; however this process of adaptation can take days or weeks. During this time, catch rates will fall independently of the true abundance of the fish. Such changes in catchability make it challenging to track stock trends based on fishery-dependent data and can then complicate efforts to assess the status of populations.

4.10 Sea Level Rise

Sea level rise is expected to directly impact many fishing communities throughout the region (see map). Given the close proximity of these communities to the coast, infrastructure and businesses closely tied to commercial and recreational fishing industries will be vulnerable. Communities will be disproportionately affected (Weiss et al. 2011), but projections show that coastal communities will be increasingly impacted by submergence, erosion, and coastal flooding, all directly impacting commercial and recreational fishing infrastructure (Gesch et al. 2009). There may be a need to relocate critical infrastructure, such as piers, docks, and seafood markets. A recent study by Colburn et al. (2016) establishes a set of social indicators to assess the impact of sea level rise on critical fishing infrastructure. They found several coastal communities in the South Atlantic to be considered highly vulnerable, with southeastern Florida and the Florida Keys having the highest concentration of impacted communities.

4.11 Socio-Economic Impacts

By altering the abundance, distribution, and phenology of marine fish in the southeast U.S., climate variability and change will also affect the fishing opportunities available in the region. These changes may drive social and economic transitions for coastal towns and cities that rely on fishing for their culture, identity, and economy (Pinsky and Fogarty 2012). For example, changes in distribution can increase travel time and costs for fishers as previously nearby fishing grounds shift further away. However, the fishing industry may also see opportunities to catch new species that arrive, and may choose to adapt processing and fishing gear and infrastructure to take advantage of these opportunities. The choices available to the fishing industry are strongly constrained by social, economic, and regulatory factors, and given the uncertainties of future changes, fishermen may cope in part by diversifying among fisheries, joining together in cooperatives, and diversifying among sources of income. Other management measures that can foster adaptation include transferable quotes, vessel buybacks, effort to promote alternative and underdeveloped fisheries, reduction of perverse subsidies, and endowment funds.

In addition, because fishing is a social-ecological system, the impacts of climate change must be considered in light of feedbacks between the behavior of fishers and the species they exploit. Reduced fishing on newly arrived species will hasten their establishment, for example, and may prove beneficial in the long run if it allows a viable fishery to develop more quickly. On the other hand, continued fishing on trailing edge populations might prolong an existing fishery and ease the economic transition to new species, but may also trigger a disruptive population collapse.

5. Knowledge Gaps and Research Priorities Related to Management Needs

The following areas were identified as knowledge gaps in the South Atlantic region and research should be prioritized to advance our understanding of impacts of climate variability on fisheries resources and management:

Ocean Observations

With respect to the fisheries resources in this region the most significant climatic changes are likely to be changes in circulation (in particular the strength and position of the Gulf Stream), changes in local wind fields responsible for cross shelf transport and upwelling, precipitation resulting in runoff into and changes in salinity in the estuarine systems serving as nursery habitats, sea level rise within the estuarine zones, changes in pH, oxygen, and water temperature. Both the climatic average and the degree of variability for these parameters are expected to change (or in some cases may already be changing). Monitoring networks for some if these parameters, such as precipitation, tidal heights, and littoral winds, are well established, but as we move offshore less data is available. While remote sensing data and *in situ* data collected by many organizations are helping to fill the gap, there are still significant gaps in observations from the estuaries through the US Exclusive Economic Zone that result in our inability to provide integrated nowcasts and forecasts of present and future ocean conditions. Filling these gaps is a research priority.

Improved Regional Climate Prediction

There are two additional main issues that are related to this inability to provide reliable nowcast and forecasts: 1) the availability of adequately verified and calibrated downscaled coupled models over the spatial domain of interest; and 2) making predictions on inter-decadal (versus longer) time scales. Decadal scales (10-40 yrs) are technically challenging even on basin or global scales (e.g., see World Climate Research Programme, 2013) where skill is limited and when one combines this issue with the necessity to predict on regional scales the problems are compounded. While large-scale directional change is relatively well understood (e.g. Melillo et al. 2014), integrated analyses indicating direction or rate of change occurring in the southeast region are lacking. Such analyses and addressing the inter-decadal gap are a research priority.

Species and Habitat Vulnerability to Climate Change

The lack of rigorous scientific understanding of the overall responses of South Atlantic marine communities to climate variability and change limits our ability to describe the vulnerability of resources to future conditions in the region. This lack has a number of inter-related causes. First, the magnitude of historical climate variability in our region is rather small in comparison to the interannual-to-decadal variability evident in other regions of the US (e.g., the Northeast US continental shelf or US west coast). In those regions the relationships between climate variability and fisheries have received considerably more attention (Mantua et al. 1997, Hollowed et al. 2001, Checkley and Barth 2009, Friedland and Hare 2007, Runge et al. 2010) and mechanistic understanding is more advanced. In addition there has been less systematic documentation of the overall community of marine populations along the southeastern coast of the US are lacking. While surveys of adult stocks are routine (e.g., MARMAP), the region lacks regular research surveys of zooplankton, ichthyoplankton, and hydrography that have become standard in other regions (e.g., EcoMon in Northeast and CalCOFI along the west coast). Projections suggesting that species' distributions will shift poleward or shoreward with future warming in the region are based on basic temperature-preference assumptions or laboratory studies on adult fish (e.g., Grieve at al. 2016), and such assumptions may be inadequate to describe species responses in the dynamic marine environment. Lack of time series data and a limited history of fisheries oceanographic work in the region regarding the influence of climate processes on ocean physical and biological parameters challenge our ability to make projections about ecological responses to future change. Obtaining these data and conducting this research should be a priority.

Predictions of future physical states of the South Atlantic can be used in conjunction with information on vulnerability of species to help characterize the future states of marine and coastal ecosystems and the specific population responses. For example, the risk assessment framework proposed by Gaichas et al. (2014) combines quantitative changes in physical variables (e.g., temperature, salinity, stratification) with life history characteristics of key species to predict the level of risk to different fish communities. Such an assessment would be helpful for prioritizing research activities in the region and for highlighting the potential vulnerabilities to fishing-dependent communities. NOAA Fisheries has developed a framework for conducting vulnerability assessments and has completed them in the Northeast Region (Morrison et al. 2015). This framework has been internally vetted and peer-reviewed (Hare et al. 2016), and could be used for carrying out vulnerability assessments for the Southeast Region.

Social Impacts and Fisheries Responses to Climate Variability

Changes in the distribution, abundance, vulnerability and availability due to environmental variability and climate change will result in a gradation of socio-economic impacts in the southeastern U.S. depending upon whether the fish and fishermen are able to move with shifting habitats. Important questions need to be answered. Will the fish move so far from their traditional fishing grounds that the fishermen either have to move with the fish to new jurisdictions, target other species, or stop fishing? Will fishermen have to change techniques and gear as the catchability (availability and vulnerability) of the species change? What will happen to existing fish processing and transportation infrastructure as species change distribution and abundance? Will new infrastructure need to be developed in new fishing areas? What will be the change in associated overhead and profit? How will families and communities respond to the change in fisheries? Answering these questions is critical to management and must be an ecological and sociological research priority.

A number of recent studies have provided a groundwork for understanding human community response to climate change, though these methods largely have yet to be applied to the South Atlantic region. Jacob and Jepson (2009) used the Fish Stock Sustainability Index (FSSI) to understand the combined levels of sustainability of stocks on which community incomes depend. The Northeast region recently received $5 million to support projects largely related to understanding the impacts of climate change on fishing communities (http://www.st.nmfs.noaa.gov/ecosystems/climate/northeast-shelf-climate-impact), and it is possible that the South Atlantic could apply some of the resulting methodologies to the region. Jepson and Colburn (2013) recently developed a suite of community vulnerability indicators for the entire U.S. Atlantic coast, and these can serve as a basis for monitoring changes due to climate and other pressures on the marine ecosystem.

Indicator Selection

The Integrated Ecosystem Assessment process has been successfully applied in other FMC regions (e.g. the Gulf of Mexico) and a process of indicator selection employing Primary, Data and Communication criteria in this context was described by Fletcher et al. (2014). The process has been successfully applied to both climate parameter indicators and to ecological indicators. It can and should be emulated by the SAFMC. The selection (and possibly development) of a parsimonious set of indicators needs to be a research priority.

Major Observation Gaps

There are large gaps in the biological data required for an IEA of this region. As noted earlier there is a dearth of plankton data (with the requisite synoptic physical data) over much of the region. There are regular demersal fish surveys, but these surveys are limited in time and space. They do not provide the data needed to evaluate apparent changes in environmental conditions in a coherent manner as they are not standardized surveys that repeatedly sample the same stations at regular intervals. The same can be said with respect to forage fishes not targeted by the commercial fleet. Overall in comparison to some other regions fisheries independent sampling is generally lacking in the SE and obtaining these data should be a research priority.

An additional problem is that catches (and effort estimates) are not known at the spatial and temporal resolution needed to determine relationships between the catch and the environment because only landings are reported. Vessel monitoring systems are not required, nor are there many vessels involved in cooperative research to provide needed data. Tools that would address this problem to provide the spatial and temporal resolution necessary should be a priority along with cooperative research.

Implications for Management

Informing short-term tactical management essentially requires obtaining and delivering a mechanistic understanding of climate effects on various processes at the scales at which management acts. In the Gulf of Mexico, operational models are currently being developed to predict climate effects on the dynamics of select species in the snapper-grouper complex. Such initiatives include an index of natural mortality for grouper species based on red tide events (Walter et al. 2013) and predictions of recruitment strength for red snapper (Karnauskas et al. 2013a). Such efforts should be expanded to the South Atlantic. These predictions can be incorporated into stock assessments for these species to inform key parameters (natural mortality and recruitment). When understanding the specific mechanisms driving population dynamics is not possible, other statistical methods can be used to make one-year-ahead predictions of population parameters (e.g., Harford et al. 2014). Applying these statistical methods to SE species (and validating the predictions made) needs to be a research priority.

Incorporating climate information into medium-term fishery management essentially entails the use of management strategy evaluation (MSE), a tool which can be used to determine whether current harvest strategies are robust to future changes. Incorporating various climate scenarios into the MSE framework depends on understanding the range of plausible future ecosystem states. For example, models of future predicted physical conditions could be used to estimate how fish recruitment will fluctuate, and these estimates could be incorporated into MSE to understand whether current practices are robust to expected changes in productivity. In the Southeast region, work is currently being carried out in both single-species and multi-species frameworks, to understand the potential effects of red tides on the Florida West Shelf. Management strategy evaluation is being used to determine whether current harvest control rules are robust to increasing episodic natural mortality events (Harford et al., in prep). Such exercises should be extended to the South Atlantic to determine whether management policies are robust to the expected changes in stock dynamics.

Inclusion of climate information in the management process can sometimes represent a significant burden on an already over-complicated management process. Including environmental forces suspected to alter population dynamics then adds an additional level of complexity to the process. A prioritization exercise should be carried out to understand where the inclusion of climate information could realistically improve the management process. In some cases, focused research programs may help us to effectively detect and respond to climate influences on populations; in others, detecting such effects may be cost-prohibitive and we may be required to focus on risk-adverse management policies. Given limited resources such a systematic prioritization effort is needed to set climate-related fisheries research priorities in the region.

Overall, adaptive decision processes in the South Atlantic that can respond to climate should evolve through increased dialogue between scientists, managers, and stakeholders, and through studies focused on when and where climate information has the greatest capacity to improve management. Initiatives such as Ecosystem Status Reports (e.g., Karnauskas et al. 2013b) can serve to motivate this dialogue and highlight to science and management communities the range of drivers that may be important to consider. Such information can be tailored to the management process; for example, in other regions various management documents are accompanied by “ecosystem considerations” summaries that then help form the basis of decision-making. We need to apply the same process in our region.

Last, as noted by Schindler and Hilborn (2015), scenario planning versus reliance upon forecast models which are likely to remain highly uncertain is likely more applicable to the problem of EBFM in the climate change context. The precautionary principle should be interpreted as requiring flexibility (versus rigidity) in any policy adopted and reliance upon adaptive management given the apparent non-stationarity in many key ecosystem relationships. The lack of information on effort and catch along with knowledge of the species vulnerabilities have generally prevented the development of environmentally adjusted catchability coefficients in the stock assessment process. Thus, the variances of the estimates of abundance of the stocks are larger than they would be if quantitative catchabilities were used. This prevents precise estimates of abundance and estimates of the status of the stocks. Therefore scenario planning is recommended and validation of the predictions made needs to remain a research priority.

6. Links to SAFMC Management Decisions and Ecosystem-Based Fisheries Management

Effective management of variable, uncertain, and non-stationary systems has received considerable attention in recent years, particularly with the recognition of climate change and variability as major concerns. General principles include the importance of 1) evaluating management approaches under a wide range of possible scenarios, 2) efforts to maintain ecosystem heterogeneity and diversity (and hence options), 3) ongoing monitoring and assessment of ecosystem state, and 4) maintaining management flexibility and responsiveness. In the context of climate variability, populations and ecosystems facing fewer non-climate stressors will tend to be more resilient to changes in climatic conditions.

Climate variability has important implications for the spatial management of marine species. Fish populations often react to changing ocean conditions. As discussed earlier in the chapter, as the ocean temperatures change, many fish species are expanding their range or shifting their distributions toward the poles or into deep areas to find cooler waters (Jones and Cheung 2014). In the South Atlantic, scientists are observing changes in the distribution of cobia which are shifting northwards during their spring migration. Available thermal habitat is also expected to increase for invasive species such as lionfish permitting the species to invade new habitats year-round in the coming decades (Grieve et al. 2016). Black sea bass are being caught further south off Florida and Walker (2016) documented an increase in probability of occurrence in recent years around Cape Canaveral, Florida which could be related to cooler near surface water resulting from more frequent upwelling events in recent years. Such events need to be investigated comprehensively. As conditions change and fluctuate, other South Atlantic fish populations could follow suit. This is particularly important because the movement of species into other jurisdictions can affect existing management plans and perhaps require modification of existing management strategies.

Changing ocean conditions have the potential to alter existing fisheries and create opportunities for new fisheries in other regions. Sometimes this can happen before managers have an opportunity to consider the potential impacts of the new fishery on the ecosystem and put appropriate management measures in place (e.g. Atlantic cobia and blueline tilefish in the Mid-Atlantic are two potential examples). As climate variability leads to range expansions and distribution shifts, new opportunities may develop leading to a cascading effect on other fish species and habitats, and highlighting the need for a precautionary approach.

The extent and degree of changes expected in the South Atlantic are not fully known and the consequences of these changes cannot always be predicted. Such changes have implications for both stock assessments and fisheries management decisions. Changes in distributions impact stock boundaries, survey indices, allocations, and fisheries operations. Each of these unknowns requires adaptive management strategies and necessitates managing for a higher level of uncertainty and proceeding with caution.

Changes in land and water use inland can also amplify climate variability impacts of fisheries. Conservation partnerships in these areas are beginning to consider how these changes inland might affect marine ecosystems and fisheries in the face of increased climate variability. SAFMC should work with large multi-organizational partnerships (e.g., South Atlantic Landscape Conservation Cooperative, Southeast Aquatic Resources Partnership, SECOORA) to identify ways coastal and inland actions can help sustain fisheries under increasing climate variability.

Climate considerations should also be incorporated into System Management Plans for Marine Protected Areas (MPAs) and Special Management Zones (SMZs). MPAs are frequently proposed as a strategy to buffer fished populations against disturbance and variability, and stabilize catches in the face of both environmental variability and management uncertainty (Allison et al. 2003, Hopf et al. 2016). Recently, several authors have reviewed how MPA design could be tailored to anticipate climate change and climate variability and provide better ecological resilience for fished populations (McLeod et al. 2009, Green et al. 2014). In general these studies presume that the major climatic impact on larval connectivity is to shorten dispersal distances (Gerber et al. 2014), so the recommendations typically center on increasing the number of MPAs and decreasing the spacing among them in an effort to improve connectivity and spread the risk of climate-related disturbances. It is also generally recommended to focus protection on locations that have historically experienced greater environmental variability, with the expectation that populations in those locations will be better adapted to the highly variable conditions of the future ocean (McLeod et al. 2009, Green et al. 2014). However, a critique of many of these broad recommendations is that they frequently lack specific ecological data to support them or to guide targeted MPA planning in a particular location (Magris et al. 2014). Again, targeted local modeling efforts would be needed to produce informative planning guidelines.

One recommendation to improve MPA implementation in a variable climate is to use a flexible marine spatial planning approach, potentially shifting protected areas in response to climate conditions (Gerber et al. 2014). However, too-frequent shifts in MPA boundaries could jeopardize a key benefit of MPAs, which is the accumulation of adult biomass and populations with a full age structure un-truncated by fishing (White et al. 2013, Barnett and Baskett 2015). These features lead to improved resilience to disturbance and thus augment population persistence (Barnett and Baskett 2015). However, MPAs could also lead to unanticipated negative impacts; for example, intense fishing outside MPAs could blunt the leading edge of a species undergoing a climate-driven range shift, slowing the shift velocity and threatening population persistence (Fuller et al. 2015). For this reason (and to improve MPA performance in general), MPA planning should always be integrated with fishery management to control harvest outside MPA boundaries (White et al. 2010, Hopf et al. 2016).

Accounting for climate-driven changes in population dynamics and in particular stock abundance also remains a challenge for future management. Variations in the climate can contribute to stock distributional shifts, stock expansions (both vertical and horizontal), changes in catchability, and alterations in vital rates – all of which can manifest themselves similarly in the quantities we observe through fishery data collection. For example, the recent increases in landings of blueline tilefish in the Mid-Atlantic region could have resulted from a northward expansion of the stock, increases in abundance of the species in the northern portion of its range, or increases in fishing effort in that region. Disentangling these effects – which often are not mutually exclusive – will thus require not only cooperation among Councils and survey efforts, but also new scientific and statistical approaches.

The development of fishery-independent surveys, particularly those that are coordinated across regions, will be helpful in parsing apart changes in fishing behavior from changes in local abundance. Increased coordination of surveys across jurisdictions will help in the detection of shifts in stock distributions. Still, fishery-independent surveys have their own set of problems relating to climate variability, as they typically rely on fixed stations or grid cells which sample an underlying environment in constant flux. Abundance indices from standardized surveys can be refined by including environmental covariates in order to remove the effect of annual variability on the apparent relative abundance. However, such methodologies must be approached with caution, particularly when the underlying mechanisms of the fish-environment relationship are unknown. Environmental variability can also have an effect on individual vital rates such as growth or maturity, which can result in increases or decreases in abundance and biomass at the population level. In such cases, including environmental covariates in the analysis of catch-per-unit-effort can result in removal of an abundance trend when it is actually present and necessary to account for. Differentiating whether environmental processes affect catchability or production (or both) will likely require additional research as well as the development of novel statistical approaches. Coordination with other management, research, and observational efforts will also be important in gaining a mechanistic understanding of climate impacts (e.g., whole watershed, cumulative impacts, SECOORA, SALCC, other Councils, see Appendix A).

Given that abundance indices and other quantities derived from fishery data generally give the most direct information on changes in population size in a stock assessment framework, the degree of accuracy of these measures will impact the derived reference points and management benchmarks. Yet even when climate-driven population impacts are tracked and well-understood, there will still be logistical issues that arise, such as how stock assessments get carried out when stocks have fluid boundaries spanning multiple jurisdictions, and how to determine allocations for stocks in cases where abundance or productivity is changing relative to boundaries.

Another issue that has concerned fishery managers for hundreds of years is obtaining an understanding the environmentally-driven causes of recruitment fluctuations, and this topic becomes increasingly relevant under changing climate conditions. Understanding recruitment fluctuations can be of particular interest for the management of fisheries that are sustained by infrequent, strong year classes (e.g., many grouper species). Given that time and resources are necessary to gain a mechanistic understanding of the environmental causes of recruitment fluctuations, it is necessary to evaluate when such information can actually improve the management process. For a stock that is operating at a biomass roughly around the theoretical maximum sustainable yield, the stock-recruitment curve (regardless of the specific parameterization – e.g., Beverton-Holt, Ricker) often approximates a horizontal line. Thus, even under situations where recruitment levels are highly stochastic, one can successfully manage a stock over the long term, in the absence of an understanding about the causes of recruitment fluctuations. When stocks managed at or around this level, additional information on recruitment predictions might help optimize quotas from year to year and thereby increase long-term yield, particularly in cases where the fishery is composed of a substantial proportion of new recruits. In other cases, where new cohorts have an influence on the fishery only after being detected by management and incorporated into quotas, such predictions may provide little benefit.

A lack of understanding of the environmental drivers of recruitment strength can become problematic when the stock-recruitment relationship breaks down; i.e., when a significant shift in average recruitment occurs.   This can be particularly problematic if a sudden downward shift in recruitment levels leads to the stock being nudged toward the (typically unknown) point where low recruitment years become more probable, collapse becomes more likely, and recovery trajectories become more uncertain. Still, depending on the severity of the shift, the nature of the fishery, and the available data with which to track such changes, management may have the capacity to respond to such recruitment regime shifts without necessarily understanding the drivers behind the change in productivity.

The most robust method for determining the value of information to the management process is to use management strategy evaluation (MSE), whereby the entire fishery system – data collection, assessment, and management – are modeled in a simulated environment. In the MSE process, a simulated natural system is subject to data collection, assessment, and management processes that approximate those used in the real world. This management system is then run forward in time to determine whether the process, when implemented over the long term, results in predetermined management goals being met. Because the simulated natural system is a "known" truth, but the management system is implemented "blindly" with only the information available in real life, the process enables one to identify where the management system has the potential to succeed or fail. One can then test, for example, whether spending resources to obtain additional data on the strength of incoming year classes will actually improve long-term yields without increasing risk of stock collapse for a given species and management system. When climate impacts on stocks are suspected, management strategy evaluation can be a useful tool for determining where research efforts are best focused to ensure that management objectives can be achieved under potentially changing conditions.

Efforts to develop indicators of the influential climate processes affecting stocks can also be helpful for informing management in the near-term scales. These indicators are often summarized in ecosystem status reports or ecosystem considerations chapters that accompany management documents. Indicators inform rates of change and, when considered as a suite, can highlight wholesale changes in ecosystem components that would be expected to reverberate through the entire system (e.g., the arrival of a previously unseen temperature regime). Typically, these indicators are not used quantitatively in determining management advice, but they can be used to refine management decisions. For example, a sudden drop in primary productivity, or a significant change in a process thought to affect recruitment of commercial stocks, might be taken into account when considering the appropriate buffer around a management benchmark. Such efforts allow the effects of climate variability to be inserted into the management process on at least some level, and represent preliminary steps toward ecosystem-based management.

With the impacts of climate becoming increasingly apparent, and the resulting recognition that stocks cannot be managed without consideration of other ecosystem components, the concept of ecosystem-based reference points has also received increased attention. However, in a region of both high biological diversity and few long-term fishery-independent data collection efforts, we often lack the ability to track trends in individual species. Tracking ecosystem components, and making management decisions based on the states of these components, represents an even more daunting challenge. To date, the most pragmatic example of an ecosystem-based reference point in the South Atlantic is the Atlantic Menhaden Technical Committee's effort to identify reference points that account for the Atlantic menhaden's role as a forage fish species. This effort has not yet led to specific recommendations, as the Committee determined that more explicit statements of ecological goals were necessary and that further research was needed to evaluate the expected performance of proposed ecological reference points. Working on comparative studies with other relatively more data-rich regions may be one way to progress in this regard

Summary Recommendations:

1. As species expand/shift their distributions due to changing ocean conditions and/or market demands, it is the Council's policy that the SAFMC will proactively work with:
    a. State agencies, other Councils, Atlantic State Fishery Commission, and NOAA Fisheries to manage species that span multiple jurisdictions.
    b. South Atlantic LCC, NOAA RISAs, Southeast Climate Science Center, and other multi-organizational partnerships.
    c. The fishing industries, fishing communities, and other interested civil stakeholders.

2. A priority list of climate indicators should be developed by NOAA or regional partners or selected that likely track ecological, social, and economic trends and status. The Council requests annual summaries of these indicators, species likely to be influenced, and fisheries trends that appear to be due to changing ocean environmental conditions in the South Atlantic ecosystem.

3. Climate change requires the consideration of tradeoffs. Changing ocean conditions necessitate responses ranging from increasing buffers due to a higher level of uncertainty to adjusting quotas upward or downward to account for predicted and realized increases or decreases in productivity.

4. Given the uncertainty of climate impacts, the precautionary principle should be invoked as possible for future management decisions on issues that can be influenced by climate change.

5. Careful scientific and management evaluation should be undertaken as new fisheries develop, including consideration of how to avoid harmful impacts on essential fish habitat.

Summary Research Needs Addressing Climate Variability and Fisheries

1. Scientific research and collection of data to further understand the impacts of climate variability on the South Atlantic ecosystem and fish productivity must be prioritized. This includes research on species vulnerabilities in terms of distribution, habitat, reproduction, recruitment, growth, survival, and predator-prey interactions.

2. As appropriate, climate data and the effects of climate variability should be integrated into stock assessments. Climate impacts could also be a focus of the new proposed stock assessment research cycle.

3. More three dimensional ocean observations of ocean conditions are needed to characterize the coastal-estuarine-ocean habitats.

4. Management Strategy Evaluations are desired to allow the Council to analyze potential regional climate scenarios and determine whether current harvest strategies are robust to future changes.

5. Greater understanding of the socio-economic impacts and fisheries responses to climate variability is needed.

6. Characterization of offshore ocean habitats used by estuarine dependent species that may be useful in developing ecosystem models.

7. Literature Cited

Able, K. W. and M.P. Fahay. 2010. Ecology of estuarine fishes: temperate waters of the western North Atlantic. Johns Hopkins University Press, Baltimore, MD.

Aiken, C. M., S. A. Navarrete, and J. L. Pelegrí. 2011. Potential changes in larval dispersal and alongshore connectivity on the central Chilean coast due to an altered wind climate. Journal of Geophysical Research Biosciences 116: 2156-2202.

Allison, G.W., Gaines, S.D., Lubchenco, J. and H.P. Possingham. 2003. Ensuring persistence of marine reserves: catastrophes require adopting an insurance factor. Ecological Applications 13: S8-S24.

Andrello, M., D. Mouillot, S. Somot, W. Thuiller, and S. Manel. 2015. Additive effects of climate change on connectivity between marine protected areas and larval supply to fished areas. Diversity and Distributions 21: 139-150.

Armsworth, P.R. 2002. Recruitment limitation, population regulation, and larval connectivity in reef fish metapopulations. Ecology 83: 1092-1104.

Atkinson, L. P., T. N. Lee, J. O. Blanton, and W. S. Chandler. 1983. Climatology of the southeastern United States continental shelf waters, J. Geophys. Res., 88, 4705–4718.

Bacheler N.M. and J.C. Ballenger. 2015. Spatial and temporal patterns of black sea bass sizes and catches in the southeastern United States inferred from spatially explicit nonlinear models. Marine and Coastal Fisheries: Dynamics, Management, and Ecosystem Science 7:523-536.

Bane, J.M., Jr. and W.K. Dewar. 1988. Gulf Stream biomodality and variability downstream of the Charleston Bump. J. Geophys. Res., 93, 6695-6710.

Barnard, A.H., Stegmann, P.M., and Yoder, J.A. 1997. Seasonal surface ocean variability in the South Atlantic Bight derived from CZCS and AVHRR imagery. Continental Shelf Research 17: 1181-1206.

Barnett, L.A.K. and M.L. Baskett. 2015. Marine reserves can enhance ecological resilience. Ecology Letters 18: 1301-1310.

Bell, R.J., D.E. Richardson, J.A. hare, P.D. Lynch, and P.S. Frantoni. 2015. Disentangling the effects of climate, abundance, and size on the distribution of marine fish: an example based on four stocks from the Northeast US shelf. ICES Journal of Marine Science 72(5): 1311-1322.

Blanton, J. O., Schwing, F. B., Weber, A. H., Pietrafesa, L. J., and Hayes, D. W. 1985. Wind stress climatology in the South Atlantic Bight. In: Atkinson, L. P., Menzel, D. W., and Bush, K. A. (eds.). Oceanography of the southeastern US continental shelf. American Geophysical Union, Washington. Pp. 10-22.

Blanton, B. O., Aretxabaleta, A. L., Werner, F. E., and Seim, H. E. 2003. Monthly climatology of the continental shelf waters of the South Atlantic Bight. Journal of Geophysical Research 108:3264. doi:10.1029/2002JC001609, C8.

Botsford LW, White JW, Coffroth M-A, Jones GP, Paris C, Planes S, Shearer TL, and Thorrold S. 2009. Connectivity and resilience of coral reef metapopulations in MPAs: matching empirical efforts to predictive needs. Coral Reefs 28: 327-337.

Botsford, LW, Holland MD, Samhouri JF, White JW, and Hastings A. 2011. Importance of age structure in models of the response of upper trophic levels to fishing and climate change. ICES Journal of Marine Science 68: 1270-1283.

Botsford L.W., M. D. Holland, J. C. Field, and A. Hastings. 2014. Cohort resonance: a significant component of fluctuations in recruitment, egg production, and catch of fished populations. ICES Journal of Marine Science 71: 2158-2170.

Brander, K. 2010. Impacts of climate change on fisheries. J. Mar. Syst. 79:389–402.

Bruno, J.F., Selig, E.R., Casey, K.S., Page, C.A., Willis, B.L., Harvell, C.D., et al. 2007. Thermal Stress and Coral Cover as Drivers of Coral Disease Outbreaks. PLoS Biol 5(6): e124. doi:10.1371/journal.pbio.0050124

Bryson, R. A. and Hare, F. K. 1974. Climates of North America. World Survey of Climatology, Volume 11. Elsevier, Amsterdam. 45 pp.

Buchheister, A., Miller, T.J., Houde, E.D., Secor, D.H., and Latour, R.J. 2016. Temporal dynamics of Atlantic menhaden (*Brevoortia tyrannus*) recruitment in the Northwest Atlantic Ocean. ICES Journal of Marine Science. 73(4), 1147–1159. doi:10.1093/icesjms/fsv260

Calosi, P., S. Melatunan, L. Turner, Y. Artioli, R. Davidson, J.J. Byrne, M.R. Viant, S. Widdicombe, and S.D. Rundle. 2017. Regional adaptation defines sensitivity to future ocean acidification. Nature Communications 8: 13994. DOI: 10.1038/NCOMMS13994

Canning-Clode, J., Fowler, A.E., Byers, J.E., Carlton, J.T., and Ruiz, G.M. 2011. 'Caribbean Creep' chills out: climate change and marine invasive species. PLoS ONE 6(12): e29657.

Castelao, R.M., 2011. Intrusions of Gulf Stream waters onto the south Atlantic bight shelf, J. Geophys. Res., 116, C10011, doi:10.1029/2011JC007178.

Cerino, D., A.S. Overton, J.A. Rice, and J.A. Morris Jr. 2013. Bioenergetics and trophic impacts of the invasive Indo-Pacific lionfish. Transactions of the American Fisheries Society. 142 (6): 1522-1534.

Checkley, D. M., and J. A. Barth. 2009. Patterns and processes in the California Current System. Progress in Oceanography 83:49-64.

Colburn. L.L. , M. Jenson, C. Weng, T. Sera, J. Weiss, and J. Hare. 2016. Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. Marine Policy. http://dx.doi.org/10.1016/j.marpol.2016.04.030i.

Condron, A., DeConto, R., Bradley, R. S. and Juanes, F. 2005. Multidecadal North Atlantic climate variability and its effect on North American salmon abundance. Geophysical Research Letters, 32: L23703.

Cowen, R. K. and S. Sponaugle. 2009. Larval dispersal and marine population connectivity. Annual Reviews of Marine Science 1: 443-466.

Doney, S.C., M. Ruckelshaus, J. E. Duffy, J.P. Barry, F. Chan, C.A. English, H. M. Galindo, J.M.Grebmeier, A. B. Hollowed, N. Knowlton, J. Polovina, N. N. Rabalais, W.J. Sydeman, and L.D. Talley. 2012. Climate Change Impacts on Marine Ecosystems. Ann. Rev. Mar. Sci. 4: 11-37.

Durant, J. M., D.Ø. Hjermann, G. Ottersen, and N. C. Stenseth. 2007. Climate and the match or mismatch between predator requirements and resource availability. Climate Research 33: 271-283.

Edwards, M. and A. J. Richardson. 2004. Impact of climate change on marine pelagic phenology and trophic mismatch. Nature 430: 881-884.

Feely, R. A., C. L. Sabine, J. M. Hernandez-Ayon, D. Ianson, and B. Hales. 2008. Evidence for upwelling of corrosive “acidified” water onto the continental shelf. Science 320: 1490-1492. doi:10.1126/science.1155676.

Feely, R. A., S. C. Doney, and S. R. Cooley. 2009. Ocean acidification: Present conditions and future changes in a high-CO2 world. Oceanography 22: 36-47. doi:10.5670/oceanog.2009.95.

Fletcher, P.J., C.R. Kelble, W.K. Nuttle, and G.A. Kiker. 2014. Using the integrated ecosystem assessment framework to build consensus and transfer information to managers. Ecological Indicators 44:11-25. doi:10.1016/ j.ecolind.2014.03.024 2014

Fodrie, F.J., K.L. Heck, S.P. Powers, W.M. Graham, and K. Robinson. 2010. Climate related, decadal-scale assemblage changes of seagrass associated fishes in the northern Gulf of Mexico. Global Change Biology 16(1): 48-59.

Friedland, K. D., and J. A. Hare. 2007. Long-term trends and regime shifts in sea surface temperature on the continental shelf of the northeast United States. Continental Shelf Research 27:2313-2328.

Fuller, P.L., D.M. Knott, P.R. Kingsley-Smith, J.A. Morris, C.A. Buckel, M.E. Hunter, and L.D. Hartman. 2014. Invasion of Asian tiger shrimp, Penaeus monodon Fabricius, 1798, in the western north Atlantic and Gulf of Mexico. Aquatic Invasions 9 (1): 59-70.

Fuller, E., E. Brush, and M.L. Pinsky. 2015. The persistence of populations facing climate shifts and harvest. Ecosphere 6: 153.

Gaichas, S.K., J.S. Link, and J.A. Hare. 2014. A risk-based approach to evaluating northeast US fish community vulnerability to climate change. 71(8): 2323-2342.

Gerber, L. R., M. Del Mar Mancha-Cisneros, M. I. O'Connor, and E. R. Selig. 2014. Climate change impacts on connectivity in the ocean: implications for conservation. Ecosphere 5: 1-18.

Gesch, D.B., B.T. Gutierrez, S.K. Gill. 2009. Coastal elevations. In: Titus J.G. (eds.) Coastal sensitivity to sea-level rise: a focus on the Mid-Atlantic Region. A report by the U.S. Climate Change Science Program and the Subcommittee on Global Change Research, U.S. Environmental Protection Agency, Washington, 2009, pp.25–42.

Glick, P., and J. Clough. 2006. An unfavorable tide: Global warming, coastal habitats and sportsfishing in Florida. National Wildlife Federation and Florida Wildlife Federation.

Green, A.L., L. Fernandes, G. Almany, R. Abesamis, E. McLeod, P. M. Aliño, A. T. White, R. Salm, J. Tanzer, and R. L. Pressey. 2014. Designing marine reserves for fisheries management, biodiversity conservation, and climate change adaptation. Coastal Management 42: 143-159.

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

Grüss, A., D. M. Kaplan, S. Gúenette, C. M. Roberts, L. W. Botsford. 2011. Consequences of adult and juvenile movement for marine protected areas. Biological Conservation 144: 692-702.

Hare, J. A. and Able, K. W. 2007. Mechanistic links between climate and fisheries along the East Coast of the United States: explaining population outbursts of Atlantic croaker (Micropogonias undulatus). Fisheries Oceanography, 16: 31–45.

Hare J.A., Morrison W.E., Nelson M.W., Stachura M.M., Teeters E.J., Griffis R.B., et al. 2016. A Vulnerability Assessment of Fish and Invertebrates to Climate Change on the Northeast U.S. Continental Shelf. PLoS ONE 11(2): e0146756. doi:10.1371/journal.pone.0146756.

Harford, W.J., A. Grüss, M. J. Schirripa, and M. Karnauskas (in review). Designing harvest control rules to respond to episodic natural mortality increases. Fisheries.

Harford, W.J., M. Karnauskas, J. Walter, H. Liu. 2014. Nonparametric modeling reveals environmental effects on Bluefin tuna recruitment in Atlantic, Pacific, and Southern Oceans. Working Paper.
Harvell, D., Altizer, S., Cattadori, I. M., Harrington, L. and Weil, E. 2009, Climate change and wildlife diseases: When does the host matter the most? Ecology, 90: 912–920. doi:10.1890/08-0616.1

Harvell, C.D., Mitchell, C.E., Ward, J.R., Altizer, S., Dobson, A.P., Ostfeld, R.S. et al. 2002. Climate warming and disease risks for terrestrial and marine biota. Science 296: 2158–2162.

Holland, G. J. and Webster, P. J. 2007. Heightened tropical cyclone activity in the North Atlantic: natural variability or climate trend? Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences 365:2695-2716.

Hollebone AL, and M.E.Hay. 2007. Population dynamics of the non-native crab *Petrolisthes armatus* invading the South Atlantic Bight at densities of thousands m(-2). Marine Ecology Progress Series 336: 211–223.

Hollowed, A. B., S. R. Hare, and W. S. Wooster. 2001. Pacific Basin climate variability and patterns of Northeast Pacific marine fish production. Progress in Oceanography 49:257-282.

Hopf, J.K., Jones, G.P., Williamson, D.H. and Connolly, S.R. 2016. Synergistic effects of marine reserves and harvest controls on the abundance and catch dynamics of a coral reef fishery. Current Biology 26:1-6.

Jacob, S. and M. Jepson. 2009. Creating a Community Context for the Fishery Stock Sustainability Index. Fisheries. 34(5): 228-231.

Jansen, T. and H. Gislason. 2011. Temperature affects the timing of spawning and migration of North Sea mackerel. Continental Shelf Research 31: 64–72.

Jepson, M. and L.L. Colburn. 2013. Development of Social Indicators of Fishing Community Vulnerability and Resilience in the U.S. Southeast and Northeast Regions. U.S. Dept. of Commerce., NOAA Technical Memorandum NMFS-F/SPO-129, 64 p.

Karnauskas, M., J.F. Walter, and C.B. Paris. 2013a. Use of the Connectivity Modeling System to estimate movements of red snapper (*Lutjanus campechanus*) recruits in the northern Gulf of Mexico. SEDAR31-AW10. SEDAR, North Charleston, SC. 20 pp.

Karnauskas, M., Schirripa, M. J., Kelble, C. R., Cook, G. S., Craig, J. K. (eds.) 2013b. Ecosystem status report for the Gulf of Mexico. NOAA Technical Memorandum NMFS-SEFSC-653, 52 p.
Kemp, A.C., Horton, B.P., Culver, S.J., Corbett, D.R., van de Plassche, O., Gehrels, W.R., Douglas, B.C. and Parnell, A.C. 2009. Timing and magnitude of recent accelerated sea-level rise (North Carolina, United States). Geology 37(11): 1035-1038.

Kimball, M.E., Miller, J.M., Whitfield, P.E., and J.A. Hare. 2004. Thermal tolerance and potential distribution of invasive lionfish (Pterois volitans/miles complex) on the east coast of the United States. Mar Ecol Prog Ser 283: 269–278.

Kopp, R.E., Horton, R.M., Little, C. M., Mitrovica, J. X., Oppenheimer, M., Rasmussen, D. J., Strauss, B. H. & Tebaldi, C. 2014. Probabilistic 21st and 22nd century sea-level projections at a global network of tide-gauge sites. Earth's Future, 2, 383-406.

Kristiansen, T., C. Stock, K. F. Drinkwater, and E. N. Curchitser. 2014. Mechanistic insights into the effects of climate change on larval cod. Global Change Biology 20: 1559-1584,

Labosier, C. F. and S. M. Quiring, 2013. Hydroclimatology of the southeast USA, Climate Research, 57, 157-171. Doi: 10.3354/cr01166

Landsea, C. W. 2007. Counting Atlantic tropical cyclones back to 1900. EOS Transactions American Geophysical Union 88:197-202.

Landsea, C.W., Vecchi, G.A., Bengtsson, L., and Knutson, T.T., 2010. Impact of Duration Thresholds on Atlantic Tropical Cyclone Counts. Journal of Climate, 23: 2508-2519.

Lee, T.N., J.A. Yoder and L.P. Atkinson, 1991. Gulf Stream frontal eddy influence on productivity of the southeast U.S. continental shelf, J. Geophys. Res., 96 (22): 191-205.

Lett, C., S-D Ayata, M. Huret, and J-O Irisson. 2010. Biophysical modeling to investigate the effects of climate change on marine population dispersal and connectivity. Progress in Oceanography 87:106-113.

Lindeman, K.C., L.E. Dame, C.B. Avenarius, B.P. Horton, J.P. Donnelly, D.R. Corbett, A.C. Kemp, P. Lane, M.E. Mann and W.R. Peltier. 2015. Science needs for sea-level adaptation planning: comparisons among three U.S. Atlantic coastal regions. Coastal Management 43(5): 555-574.

Lowerre-Barbieri, S.K., Ganias, K., Saborido-Rey, F., Murua, H., Hunter, J.R. 2011. Reproductive timing in marine fishes: variability, temporal scales, and methods. Marine and Coastal Fisheries 3: 71-91.

Magris, R. A., R. L. Pressey, R. Weeks, and N. C. Ban. 2014. Integrating connectivity and climate change into marine conservation planning. Biological Conservation 170: 207-221.

Mann, M. E. and Emanuel, K. A. 2006. Atlantic hurricane trends linked to climate change. EOS Transactions American Geophysical Union 87:233-244.

Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis. 1997. A Pacific interdecadal climate oscillation with impacts on salmon production. Bulletin of the American Meteorological Society 78:1069-1079.

McCarney-Castle, K., Voulgaris, G., & Kettner, A. J. 2010. Analysis of fluvial suspended sediment load contribution through anthropocene history to the South Atlantic Bight Coastal Zone, U.S.A. The Journal of Geology, 118 (4): 399-416.

McLeod, E., R. Salm, A. Green, and J. Almany. 2009. Designing marine protected area networks to address the impacts of climate change. Frontiers in Ecology and the Environment 7: 362-370.

McLeod, I. M., J. L. Rummer, T. D. Clark, G. P. Jones, M. I. McCormick, A. S. Wenger, and P. L. Munday. 2013. Climate change and the performance of larval coral reef fishes: the interaction between temperature and food availability. Conservation Physiology 1: cot024

Melillo, J.M., T.C. Richmond, and G.W. Yohe, Eds., 2014: Climate Change Impacts in the United States: The Third National Climate Assessment. U.S. Global Change Research Program, 841 pp. doi:10.7930/J0Z31WJ2.

Miles TN, and R. He. 2010. Temporal and spatial variability of Chl-a and SST on the South Atlantic Bight: revisiting with cloud-free reconstructions of the MODIS satellite imagery. Continental Shelf Research 30: 1951-1962.

Mills, K.E., Pershing A.J., Brown, C.J., Chen Y., and 7 others. 2013. Fisheries management in a changing climate: lessons from the 2012 heat wave in the northeast Atlantic. Oceanography 26: 191-195.

Moorman, M.C., Hoos, A.B., Bricker, S.B., Moore, R.B., García, A.M., and Ator, S.W., 2014, Appendix 1 of Nutrient load summaries for major lakes and estuaries of the Eastern United States, 2002: U.S. Geological Survey Data Series 820, 94 p., http://dx.doi.org/10.3133/ds820.

Morley, J.W., R.D. Batt, and M.L. Pinsky. 2016. Marine assemblages respond rapidly to winter climate variability. Global Change Biology. Version of Record online : 20 DEC 2016, DOI: 10.1111/gcb.13578.

Morrison, W.E., M. W. Nelson, J. F. Howard, E. J. Teeters, J. A. Hare, R. B. Griffis, J.D. Scott, and M.A. Alexander. 2015. Methodology for Assessing the Vulnerability of Marine Fish and Shellfish Species to a Changing Climate. U.S. Dept. of Commer., NOAA. NOAA Technical Memorandum NMFS-OSF-3, 48 p.

Muhling, B. A., Lee, S-K., Lamkin, J. T., and Liu, Y. 2011. Predicting the effects of climate change on bluefin tuna (Thunnus thynnus) spawning habitat in the Gulf of Mexico. ICES Journal of Marine Science, 68: 1051–1062.

Munday, P.L., J. M. Leis, J. M. Lough, C. B. Paris, M. J. Kingsford, M. L. Berumen, and J. Lambrechts. 2009. Climate change and coral reef connectivity. Coral Reefs 28: 379-395.

Munday, P. L., D. L. Dixson, M. I. McCormick, M. Meekan, M. C. O. Ferrari, and D. P. Chivers. 2010. Replenishment of fish populations is threatened by ocean acidification. Proceedings of the National Academy of Sciences USA 107: 12930-12934.

Muñoz R.C., Currin C.A., and Whitfield, P.E. 2011. Diet of invasive lionfish on hard bottom reefs of the Southeast USA: insights from stomach contents and stable isotopes. Marine Ecology Progress Series, 432, 181–193.

Nagelkerken, I. and Connell, S.D. 2015. Global alteration of ocean ecosystem functioning due to increasing human CO_2 emissions. Proceedings of National Academy of Sciences 112 (43): 13272-13277.

National Marine Fisheries Service. 2016. Fisheries Economics of the United States, 2014. U.S. Dept. of Commerce, NOAA Tech. Memo. NMFS-F/SPO-163, 237p.

National Marine Fisheries Service. 2017. South Atlantic Regional Action Plan to Implement the NOAA Fisheries Climate Science Strategy: Draft for Public Review February 2017.

Nicholls, R.J. and Cazenave, A. 2010. Sea-level rise and its impact on coastal zones. Science 328: 1517-1520.

NMFS Southeast Regional Office, 2017. South Atlantic Recreational Landings and Annual Catch Limits (ACLs): http://sero.nmfs.noaa.gov/sustainable_fisheries/acl_monitoring/recreational_sa/index.html

O'Connor, M. I., J. F. Bruno, S. D. Gaines, B. S. Halpern, S. E. Lester, B. P. Kinlan, and J. M. Weiss. 2007. Temperature control of larval dispersal and the implications for marine ecology, evolution, and conservation. Proceedings of the National Academy of Sciences USA 104: 1266-1271.
Paffenhofer, G-A, B.K. Sherman and T.N. Lee, 1987. Summer upwelling on the southeastern continental shelf of the USA during 1981: changes in distribution and abundance of particulate matter, Prog. Oceanogr. 19: 403-436.

Parker, R.O., and Dixon, R.L. 1998. Changes in a North Carolina reef fish community after 15 years of intense fishing—global warming Implications. Transactions of the American Fisheries Society 127: 908–920.

Parkinson, R. W., Harlem, P. W., & Meeder, J. F. 2015. Managing the Anthropocene marine transgression to the year 2100 and beyond in the State of Florida USA. Climatic Change 128(1-2): 85-98.

Parris A, Bromirski P, Burkett V, Cayan D, Culver M, Hall J, Horton R, Knuuti K, Moss R, Obeysekera J, Sallenger A, and Weiss J. 2012. Global Sea Level Rise Scenarios for the US National Climate Assessment. NOAA Tech Memo OAR CPO-1.

Philippart C.J.M., van Aken H.M., Beukema J.J., Bos O.G., Cadee G.C., Dekker, R. 2003. Climate-related changes in recruitment of the bivalve *Macoma balthica*. Limnol. Oceanogr. 48:2171–85

Pinsky, M. L. and M. Fogarty. Lagged social-ecological responses to climate and range shifts in fisheries. Climatic Change Letters 115(3): 883-891.

Pinsky, M.L., Worm, B., Fogarty, M.J., Sarmiento, J.L., and Levin, S.A. 2013. Marine taxa track climate velocities. Science 341: 1239-1242 (and SEAMAP data)

Pörtner, H.O. 2002. Climate variations and the physiological basis of temperature dependent biogeography: systemic to molecular hierarchy of thermal tolerance in animals. Comparative Biochemistry and Physiology Part A 132: 739-761.

Pörtner, H.O. and R. Knust. 2007. Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science 315: 95-97.

Rijnsdorp, A.D., Peck, M.A., Engelhard, G.H., Möllmann, C., and Pinnegar, J.K. 2009. Resolving the effect of climate change on fish populations. ICES Journal of Marine Science 66: 1570-1583.

Runge, J. A., A. I. Kovach, J. H. Churchill, L. A. Kerr, J. R. Morrison, R. C. Beardsley, D. L. Berlinsky, C. S. Chen, S. X. Cadrin, C. S. Davis, K. H. Ford, J. H. Grabowski, W. H. Howell, R. B. Ji, R. J. Jones, A. J. Pershing, N. R. Record, A. C. Thomas, G. D. Sherwood, S. M. L. Tallack, and D. W. Townsend. 2010. Understanding climate impacts on recruitment and spatial dynamics of Atlantic cod in the Gulf of Maine: Integration of observations and modeling. Progress in Oceanography 87:251-263.

Sanford E. 1999. Regulation of keystone predation by small changes in ocean temperature. Science 283:2095–97.

Sanger, D.M., Smith, E.M., Voulgaris, G., Koepfler, E.T. and others. 2012. Constrained enrichment contributes to hypoxia formation in Long Bay, South Carolina (USA), an open water urbanized coastline. Mar Ecol Prog Ser 461:15-30.

Savidge, D.K., J.O. Blanton, T.N. Lee, and R.H. Evans. 1992. Influence of an offshore shift in the Gulf Stream on waters of the South Carolina continental shelf, J. Phys. Oceanogr., 22: 1085-1094.

Schindler, D.E. and R. Hilborn. 2015. Prediction, precaution, and policy under global change. Science. 347 (6225): 953-954.

Semmens, B.X., Buhle, E.R., Salomon, A.K., Pattengill-Semmens, C.V. 2004. A hotspot of non-native marine fishes: evidence for the aquarium trade as an invasion pathway. Mar Ecol Prog Ser 266: 239–244.

Sims, D.W., Genner, M.J., Southward, A.J., and Hawkins, S.J. 2001. Timing of squid migration reflects north Atlantic climate variability. Proceedings of the Royal Society of London B 268: 2607-2611.

Sims, D.W., Wearmouth, V.J., Genner, M J., Southward, A J. & Hawkins, S.J. 2005. Low-temperature-driven early spawning migration of a temperate marine fish. Journal of Animal Ecology 73: 333–341.

Sobeck, E. 2015. NOAA Fisheries Climate Science Strategy. NOAA, NMFS OST. 24 p.

Southwick Associates. 2013. *Sportfishing in America: An Economic Force for Conservation.* Produced for the American Sportfishing Association (ASA) under a U.S. Fish and Wildlife Service (USFWS) Sport Fish Restoration grant (F12AP00137, VA M-26-R) awarded by the Association of Fish and Wildlife Agencies (AFWA), 2012.

St. Mary, C. M., C. W. Osenberg, T. K. Frazer, W. J. Lindberg. 2000. Stage structure, density dependence, and the efficacy of marine reserves. Bulletin of Marine Science 66: 675-690.

Stramma, L., E.D. Prince, S. Schmidtko, J. Luo, J.P. Hoolihan, M. Visbeck, D.W.R. Wallace, P. Brandt, and A. Kortzinger. 2012. Expansion of oxygen minimum zones may reduce available habitat for tropical pelagic species. Nature Climate Change 2: 33-37.

Sunday, J.M., Bates, A.E., and Duty, N.K. (2012) Thermal tolerance and the global redistribution of animals. Nature Climate Change 2: 686-690

Sunday, J.M., Pecl, G.T., Frusher, S., Hobday, A.J., and 14 others. 2015. Species traits and climate velocity explain geographic range shifts in an ocean-warming hotspot. Ecology Letters 18:944-953.

Tebaldi, C., B. H. Strauss, and C. E. Zervas. 2012. Modeling sea-level rise impacts on storm surges along US coasts. Environmental Research Letters 7.

U.S. National Research Council. 1998. Sustaining marine fisheries. A report of the Committee on Ecosystem Management for Sustainable Fisheries. Ocean Studies Board, Commission on Geosciences, Environment and Resources, National Research Council. Washington, D.C. National Academy Press, 167 pp.

Verity, P.G., Alber, M, and Bricker, SB. 2006. Development of hypoxia in well-mixed subtropical estuaries in the southeastern USA. Estuaries and Coasts 29:665-673.

Walker, M.F. 2016. Species distribution modeling of Black Sea Bass (Centropristis striata) and White Grunt (Haemulon plumierii). College of Charleston Thesis.

Wall, C.C., F.E. Muller-Karger, and M.A. Roffer. 2009. Linkages between environmental conditions and recreational king mackerel (*Scomberomorus cavalla*) catch off west-central Florida. Fisheries Oceanography 18 (3): 185-199.

Walter, III, J.F., S.R. Sagarese, W.J. Harford, A. Grüss, R.P. Stumpf, M. C. Christman. 2015. Assessing the impact of the 2014 red tide event on red grouper (Epinephelus morio) in the Northeastern Gulf of Mexico. SEDAR42-RW-02. SEDAR, North Charleston, SC. 13 pp.

Weber, A. H. and Blanton, J. O. 1980. Monthly mean wind fields for the South Atlantic Bight. Journal of Physical Oceanography 10:1256-1263.

Weiss J.L., J.T. Overpeck, B. Strauss. 2011. Implications of recent sea level rise science for low-elevation areas in coastal cities of the coterminous U.S.A, Climate Change 105: 635–645.

Wendland, W. M. and Bryson, R. A. 1981. Northern hemisphere airstream regions. Monthly Weather Review 109:255-270.

White, J.W., Botsford, L.W., Moffitt, E.A., Fischer, D.T. 2010. Decision analysis for designing marine protected areas for multiple species with uncertain fishery status. Ecological Applications 20: 1523-1541.

White, J.W., Botsford, L.W., Hastings, A., Baskett, M.L., Kaplan, D.M., Barnett, L.A.K. 2013. Transient responses of fished populations to marine reserve establishment. Conservation Letters 6: 180-191.

White, J. W. 2015. Marine reserve design theory for species with ontogenetic migration. Biology Letters 11: 20140511.

Whitfield PE, Hare JA, David AW, Harter SL, Muñoz RC, Addison CM (2007) Abundance estimates of the Indo-Pacific lionfish Pterois volitans/miles complex in the Western North Atlantic. Biological Invasions, 9, 53–64.

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

Wickes, L. 2016. 2016 State of the Science Workshop Report. Southeast Ocean and Coastal Acidification Network (SOCAN). Charleston, SC.

Wieland, K., Jarre-Teichmann, A., Horbowa, K. 2000. Changes in the timing of spawning of Baltic cod: possible causes and implications for recruitment. ICES Journal of Marine Science, 57: 452–464.

World Climate Research Programme. 2013. Report of the International workshop on seasonal to decadal prediction. May 13-16, 2013, Toulouse, France. WCRP Report No. 23/2013.

Wuenschel, M. J., Hare, J. A., Kimball, M. E., & Able, K. W. 2012. Evaluating juvenile thermal tolerance as a constraint on adult range of gray snapper (Lutjanus griseus): a combined laboratory, field and modeling approach. Journal of Experimental Marine Biology and Ecology 436: 19-27.

Wu, X., Voulgaris, G. and Kumar, N. In review. Parameterization of Synoptic Weather Systems in the South Atlantic Bight for modeling applications. Ocean Dynamics (manuscript no: ODYN-D-16-00113R1)

Appendix A

Useful links to other regional efforts including associated with climate impacts:

a. IOOS/SECOORA: www.secoora.org
b. NOAA Fisheries National Climate Strategy: http://www.st.nmfs.noaa.gov/ecosystems/climate/national-climate-strategy
c. NOAA Fisheries South Atlantic Climate Science Regional Action Plan: http://www.st.nmfs.noaa.gov/ecosystems/climate/rap/index
d. NOAA Ecological Forecasting Roadmap: http://oceanservice.noaa.gov/ecoforecasting/
e. Oceanadapt for tracking changes in species distribution (http://oceanadapt.rutgers.edu)
f. Bonefish Tarpon Trust: http://www.bonefishtarpontrust.org/research-programs/research-programs.html
g. Audubon Society: http://www.audubon.org/conservation/climate-change
h. LLC Conservation Blueprint: http://www.southatlanticlcc.org/blueprint/
i. National Science Foundation Coastal SEES: https://www.nsf.gov/funding/pgm_summ.jsp?pims_id=504816
j. Virtual Climate Adaptation Library: http://research.fit.edu/sealevelriselibrary/