ANALYZING THE SPATIAL DISTRIBUTION OF FISH SPECIES ALONG THE MID AND SOUTH ATLANTIC BIGHTS AND PROJECTING FUTURE DISTRIBUTIONS UNDER A CLIMATE CHANGE SCENARIO

by

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Student Signature: ____________________________       Date: ____________

Advisor Signature: ____________________________       Date: ____________

Duke University
NICHOLAS SCHOOL OF THE ENVIRONMENT
EXECUTIVE SUMMARY

As anthropogenic climate change increases the temperatures of the world’s oceans, the survival rates, spatial distribution, and phenology of marine species are adversely impacted. Shifts in temperature will impact organisms with smaller thermal windows, and shifts will mostly occur at the extremes of the environmental envelopes for most species. Thus, most previous research on this topic occurs in Northern waters such as the Northeast United States and Alaska, and little is understood about the impacts of anthropogenic climate change on species distributions in the South Atlantic Bight and Mid Atlantic.

Previous studies have identified the potential for poleward shifts as species search for cooler waters, yet the unique oceanographic conditions of the South Atlantic and Mid Atlantic Bight, and the unique physiology of southern species may lead to different patterns. Studying the potential for future distribution shifts in this region is important for several reasons. First, as species shift outside of their typical ranges in the North Atlantic Bight, these areas may see an influx of southern species. Second, the waters along the Mid Atlantic and South Atlantic Bight are ecologically and economically significant areas, with fisheries providing substantial revenue for the region. Therefore, the objective of this Master’s Project was to 1) identify historical shifts in seven commercially managed species’ distributions as they are related to natural climate variations and changes in Sea surface temperatures; 2) predict future species distributions under the RCP 8.5 climate change scenario.

Data on species presence were obtained from the Southeast Area Monitoring and Assessment Program. Information in the dataset included species presence and absence, weight, total number, and date collected, as well as in situ oceanographic data that were not used for this analysis. Environmental and habitat data were downloaded for each trawl from the HYCOM SST dataset and the Nature Conservancy’s Bottom Habitat Assessments, respectively. Two natural climate variations, the Atlantic Multidecadal Oscillation and the North Atlantic Oscillation, were also included in analysis to better understand the influence of natural fluctuations in ocean temperatures compared to anthropogenic warming.

First historical shifts in the weighted mean center of latitude were calculated in ArcGIS. The mean center of latitude was calculated for each year for each species. A regression analysis was performed in R to understand the relative influence of annual AMO and winter and annual NAO indexes, as well as annual average SST for the region. Next, a random forest analysis was used to identify the influence of Bottom temperature, salinity, habitat, and the climate variations on the presence and absence of each species. The random forest outputs were then used to predict present species distributions and future distributions under the RCP 8.5 scenario. Future oceanographic conditions were downloaded from the NOAA ESRL Climate Change Data Portal website, and statistically downscaled using the ‘delta’ method to produce high resolution future conditions. These results were used to predict future species distributions by using the Marine Geospatial Ecology Toolbox for ArcMap 10.1, as well as changes in species presence from the current period.

Results showed that several historical shifts in mean center of latitude are significantly correlated with the AMO for two species, and SST for one species. Historically, five of the seven species have shifted southward, and two have shifted northward, however none of these shifts were significant. Results from the future predictions show varied shifts in species ranges.
depending on the season, location, and importance of salinity and bottom temperature on species presence. Projected shifts in distributions may influence the seasonal migrations for Summer Flounder, where the changing ocean conditions cause shifts in probability of presence that oppose their seasonal migrations. Additionally, salinity was the most important predictor variable for most of the species studied. Finally, the unique oceanographic conditions of the South Atlantic and Mid Atlantic Bight lead to different projected future distributions than previous studies.

In total, the Mid Atlantic and South Atlantic Bight are expected to experience increased ocean warming and salinity levels in the near future as a result of anthropogenic climate change. Consequently, species will shift distributions depending on their preferred temperature and salinity range, the season, and the necessity of environmental variables on their distribution. Our results highlight the importance of running future distribution models at regional scales, for the impacts of changing climates on South Atlantic species varies from the trends identified in other analyses. Finally, his study demonstrates the importance of climate and fisheries research in the Mid-Atlantic and South-Atlantic Bight and emphasizes need for future research examining the magnitude and direction of future species distributions.

ABSTRACT

As anthropogenic climate change increases the temperatures of the world’s oceans, the survival rates, spatial distribution, and phenology of marine species are adversely impacted. This study evaluates the potential effects of anthropogenic climate change on seven commercially regulated fish species along the South Atlantic and Mid-Atlantic Bight. Coupling random forest models with the outputs from 27 climate models, this study projects the future distribution of species using bottom temperature, salinity, substrate type and AMO and NAO indices. Results indicate that species distribution shifts vary depending on the season, the species preferred temperature range, and the relative importance of habitat and salinity for the species.
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INTRODUCTION

I. The impacts of ocean warming on marine species

Over the last several decades, anthropogenic greenhouse gas emissions have driven large increases in atmospheric and ocean temperatures. Globally, the ocean’s upper 75 meters warmed by .11 °C per decade between 1971 to 2010, and in the Northern Hemisphere, the period from 1983-2012 was the hottest period of the previous 1400 years (IPCC AR5, Rhein et al, 2013). The observed impacts of global warming on earth's biological systems include changes in species phenology and shifts in species distributions (Parmesan & Yohe 2003). For marine fishes, climate change influences species abundance and distribution, through changes in growth and survival (Perry et al 2005).

While the impacts of anthropogenic climate change on the world's oceans range from changing dissolved oxygen levels (Schmidtko et al 2017) to increased ocean acidification (Johnson & White 2014), the influences of increased ocean temperatures on species ranges has been demonstrated in numerous studies (Parker & Dixon 1998, Brander et al 2003, Perry et al 2005, Mueter & Litzow 2008, Nye et al 2009, Toal & Fisher 2009, Figueira & Booth 2010, Fodrie et al 2020). In particular, temperature influences the behavior, metabolism and ecology of fish species, and ultimately determines the ecological range, or preferred habitat of many species (Magnusus & DeStasio 1997, Hare et al 2012a).

Studies measure the impacts of ocean warming on animals by considering the species’ oxygen capacity and limited thermal tolerance (Portner et al 2010). Shifts in temperature will impact organisms with smaller thermal windows more drastically because those species are less tolerant of temperature fluctuations. Similarly, shifts will mostly occur at the extremes of the environmental envelopes for most species. Thus, most previous research on this topic occurs in Northern waters such as the Northeast United States and Alaska (Portner et al 2010, Moerlein & Carothers 2012).

Researchers at the Northeast Fisheries Science Center have identified the historic impacts of shifting oceanographic conditions on the distribution of commercially regulated species in the Northeast region. Their work identified the importance of natural climate variations, such as the Atlantic Mutidecadal Oscillation (AMO) and the North Atlantic Oscillation (NAO), as well as
anthropogenic warming and salinity increases on the distribution of marine species. Their results show that, as a consequence of increasing temperatures and natural variations, species have shifted farther north and deeper in search for cooler waters.

II. Studying the Mid-Atlantic and South Atlantic Bight

Although most previous research in the United States has focused on the Northeast and Gulf of Maine, understanding the magnitude and direction of southern species shifts is critical as well. As species shift outside of their typical ranges in the Northeast, these areas may begin to see an influx of species from southern waters. Additionally, the waters off of the Mid Atlantic and South Atlantic Bight are ecologically and economically significant (NOAA 2014). Cape Hatteras, NC, represents a biogeographic boundary where the meeting of the warmer Gulf Stream and the colder Labrador Current leads to increased levels of productivity (Aller et al 2002) and diversity (Glen & Ebbesmeyer 1994). This area represents the southern boundary for many northern species ranges and the northern boundary for southern species (Briggs & Bowen 2012). These conditions and the Gulf Stream’s proximity to shore create an environment that allows for productive commercial (Steve et al 2001) and recreational fisheries. In 2014 alone, the Atlantic and Gulf of Mexico commercial fisheries landed $59 million worth of catch. Thus, understanding the historic and potential future range shifts of commercial species and how these relate to changing environmental conditions could have significant management implications. As species shift out of traditional areas, fishers may be faced with lost access to stocks, and regional managing bodies may have to rethink existing static management strategies.

III. Objectives of this project

This study documents the relationship between environmental conditions and commercial fish species presence along the South Atlantic Bight and Mid Atlantic Bight and projects future species distributions under a particular climate change scenario. We studied the presence of seven commercially regulated fish species along the South Atlantic and Mid Atlantic Bight. Random forest analyses were used to determine the relationship between species presence and salinity, bottom temperature, and substrate type as well as two climate indices (AMO and NAO). These models were then utilized to predict future species presence under the RCP 8.5 climate
change scenario (Guisan & Thuiller 2005). The resulting predictive models demonstrate several key findings: (1) both natural climate variations and sea surface temperatures influence the historical mean latitude of several species; (2) differing oceanographic conditions in the Mid Atlantic Bight and South Atlantic Bight lead to different projected future species distributions; (3) future shifts in probability of presence vary in intensity and direction depending on the season, location, and importance of environmental variables for the species; (4) projected shifts may influence seasonal migrations for some species; (5) salinity is largely important for predicting species distributions.

METHODS

I. Species Data

Species distribution data were obtained from the Southeast Area Monitoring and Assessment Program- South Atlantic (SEAMAP) bottom trawl survey dataset (seamap.org). Fisheries independent surveys were collected between 1990 and 2014 in inshore strata (4.6-9.1m depth) from Cape Hatteras, North Carolina to Cape Canaveral, Florida in the spring and fall of each year. Spring surveys were conducted in April and May and fall surveys were conducted in September, October and November. In total, 102,035 tows were collected in the spring and 114,982 tows were conducted in the fall. Species presence, absence and count data were recorded for 260 species. Collections were made at randomly selected sites in predefined strata (24 total). The number of stations allocated to each stratum was proportional to its area. Sampling was conducted using the 22.9 m R/V Lady Lisa, using paired 22.9m mongoose-type Falcon trawls, with 91.4m three-lead bridles attached to pairs of 3.0 m x1.0m wooden chain doors. Headropes were 22.0 m in length and footropes were 22.9m in lengths. Trawl bodies were constructed of #15 twine and had 45mm stretch mesh. Cod ends were constructed of #30 twine with 39mm stretch mesh. A tickler chain was attached to each door. Each tow was 20 minutes duration.

Seven marine fish species were selected for modeling. After limiting the dataset to only priority species (as determined by SEAMAP), commercially relevant species that occurred in at least 500 tows were selected for the final analysis.
II. **Observing historical shifts in the Mean Center of Latitude**

In order to understand the historic behavior of the selected species, a mean center of latitude was calculated for each species over the survey period using the mean centroid function in ArcMap 10.4.1. Mean center was weighted by the number of tows during the year the biomass for each species. We ran a linear regression in R to test the relationship between mean center of latitude and AMO, NAO, winter NAO, and average SST for the study area. See below for a discussion of AMO and NAO. Average SST was downloaded using the Create Climatological Raster tool for the MGET toolbox. A 20 kilometer buffer was applied to all of the study points and a spring and fall climatological raster was downloaded for April May and June (Spring) and October, November and December (Fall) using the AVHRR SST model. The average SST was calculated for the spring and fall of each year.

III. **Obtaining environmental and habitat variables**

For each specific trawl set, salinity, habitat type (substrate), bottom temperature, and average AMO and NAO (yearly average and winter average) were added to the dataset as predictor variables. Salinity has been shown to be an important predictor for species presence, and has important implications for climate change research, so it was included with bottom temperature and habitat as a predictor variable (Hurst & Conover 2002). Bottom temperature and salinity were obtained using the MGET toolbox for ArcGIS 10.1 (Roberts et al 2010); both were downloaded for the specific trawl date from the HYCOM dataset (hycom.org). HYCOM is a dynamic ocean model, which incorporates satellite and buoy data, allows for high resolution 4-D datasets, and does not include clouds in any of the data. Because trawls were collected on the ocean floor and most of the species are either pelagic or benthic species, the HYCOM modeled data was the most appropriate dataset to use. Remotely sensed satellite data only gathers information on the surface of the water, proving less useful for this study.

Yearly AMO and winter and Yearly NAO indices were added to the dataset based on the year collected (Hurrel et al 2016). The AMO is a natural climate variation that occurs on a decadal scale (20-40 years) and influences the North Atlantic’s sea surface temperature by about .56 °C at each extreme (Knight et al 2006). Currently, the AMO is in a warm period, which corresponds with increased sea surface temperatures in the Atlantic. The NAO is a pressure and
circulation pattern, which is a measurement of the sea surface pressure differences between the Subtropical High and Subpolar Low. A positive NAO phase is associated with warmer temperatures in the Eastern United States, with the opposite pattern occurring in negative phases (Hurrel 1995). Research has indicated that the most variance in the NAO occurs in the winter months, so the winter NAO (DJFM) was also used for analysis. These naturally occurring climate variations could influence the distribution of species throughout the South Atlantic, and it is important to consider the impacts of natural climate variations as well as anthropogenic warming when attempting to attribute and detect the causes of species distribution shifts.

Habitat substrate was obtained from the Nature Conservancy’s South Atlantic Bight (the Nature Conservancy 2015) and North Atlantic Bight Marine Assessment as a part of the larger Northwest Atlantic Marine Ecoregional Assessment (Greene et al 2010). The available habitat datasets included bathymetry, seabed forms, hard bottom, ecological marine units and substrate for the Southeast and bathymetry, benthic habitat, benthic sediments, seabed forms, ecoregions, ecological marine units and substrate for the Northeast. Although this research would have benefited from using ecological marine units, the southeast study and northeast study did not have a continuous nomenclature for this variable. Ultimately, substrate was used as the benthic habitat variable because it was the only habitat variable that was consistently sampled in both assessments, thus covering the entire range of this study (Figure 1). Substrate type was coded using a numeric code and joined to the presence and absence dataset. Substrate was held constant in the random forest and predictive analyses.

Figure 1. Substrate type used as the habitat variable for analysis. Substrate was taken from the Nature Conservancy’s Mid Atlantic Bight and North Atlantic Bight regional assessments
IV. Projections of future changes in BT and salinity: Applying the delta method.

In order to project future species distributions, the delta method was used to produce high resolution datasets for future bottom temperature and salinity values (Figure 2). Obtainable global general circulation models (GCMs) are relatively coarse in spatial resolution spatial resolutions (0.5 to 1.4°). This low level of resolution would prevent appropriate projections of conditions and species distributions in the area of study. To improve the spatial resolution, and therefore the projection of future habitats, we statistically downscaled coarse-resolution GCMs for the study area using a higher resolution (.08°) HYCOM climatology hindcast over the 1958-2010 period (Kang & Curchister, 2013) for bottom temperature and salinity during the spring and fall periods. The high resolution climatology hindcast was downloaded using the Marine Geospatial Ecology Toolbox. Specifically, an average climatological raster was computed for the over 1958-2010 for the spring (April, May and June) and fall (October, November and December) periods.

We used this higher resolution climatological raster and employed the delta method (Grieve et al 2016, Hamlet et al 2010, Hare et al 2012b) to downscale the low-resolution data produced by the GCMs. In this methodology, the present conditions (1958-2010) simulated by the GCMs were subtracted from the GCMs projection of conditions in the two future periods (2006-2055 and 2050-2099) to obtain the projected change in bottom temperature and salinity, or the ‘delta’ (Figure 3). The delta for the two periods can be downloaded as is from NOAA’s ESRL Climate Change Data Portal (NOAA 2017) for the spring (AMJ) and Fall (OND). The average of the 27 available GCM models was used in this analysis. All of the models were produced by groups participating in the Coupled Model Intercomparison Project (CMIP5), which generates the results for the IPCC assessments. The delta was then added to the present day high-resolution HYCOM climatology, resulting in a high-resolution prediction of future BT and salinity in the South and Mid Atlantic Bight for each of the three time periods as represented by the GCMs.
Figure 2. Example of the Delta Method for calculating high resolution future environmental rasters.

Figure 3. Change in salinity, or delta, downloaded from the NOAA ESRL climate change data portal. Delta was downloaded for two future periods, in the fall and spring, for salinity and bottom temperature.
V. Random forest analysis and future distributions

Random forest analyses were used to determine the relationship between species presence and salinity, bottom temperature, and substrate type as well as two climate indices (Annual and winter NAO and annual AMO). Random forests, an advanced type of statistical classification and regression trees (Brieman et al 1984), have been extensively utilized by ecologists because of their high accuracy with classification studies, ability to depict interactions between categorical and continuous variables, and their simple interpretation (Cutler et al 2007). Several ecological studies have used Random Forest methods for predicting species presence and absence (Prasad et al 2006, Liu et al 2012). Random forest fits multiple classification trees to a dataset, and then combines the predictions from all trees to produce more accurate classifications. Bootstrap samples are used to construct multiple trees, with each tree grown using random subset of predictors. Each random draw is done with replacement, meaning that approximately 1/3 of the samples are not used for each tree. These “out of bag” samples are used to calculate variable importance and an unbiased error rate, essentially acting as the test set for the ~2/3 of samples used in the training set. Variable importance is calculated by first randomly permuting the values of each specific predictor variable for the out of bag observations, then the new modified out of bag data are iterated down the tree in order to develop new predictions. Variable importance is the difference between the misclassification rate of the modified and original out of bag data, divided by the standard error (Cutler et al 2007).

For each species, a random forest analysis was conducted using the party package (Torsten et al 2006) for the R statistical software (R development team 2004). Each trawl in the training data set where the species of interest was present were set as 1 and all other trawls were given a value of 0. Model performance was measured by the accuracy of the predictions (percent correctly classified) and the Kappa statistic (Table 1). Partial dependence plots were constructed using the edarf package in R (Jones et al 2015). Partial dependence is a measure of the dependence of probability of presence on one predictor variable after removing the effects of the other predictor variables in the model (Cutler et al 2007).
Table 1. Accuracy and Kappa statistic results from the random forest models.

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<thead>
<tr>
<th></th>
<th>Fall</th>
<th></th>
<th>Spring</th>
<th></th>
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<tbody>
<tr>
<td></td>
<td>Accuracy</td>
<td>Kappa</td>
<td>Accuracy</td>
<td>Kappa</td>
</tr>
<tr>
<td>Atlantic Croaker</td>
<td>0.725</td>
<td>0.194</td>
<td>0.803</td>
<td>0.246</td>
</tr>
<tr>
<td>Atlantic Menhaden</td>
<td>0.879</td>
<td>0.062</td>
<td>0.8</td>
<td>0.131</td>
</tr>
<tr>
<td>Atlantic Spadefish</td>
<td>0.739</td>
<td>0.474</td>
<td>0.832</td>
<td>0</td>
</tr>
<tr>
<td>Butterfish</td>
<td>0.77</td>
<td>0.494</td>
<td>0.819</td>
<td>0.336</td>
</tr>
<tr>
<td>Spot</td>
<td>0.713</td>
<td>0.029</td>
<td>0.787</td>
<td>0.562</td>
</tr>
<tr>
<td>Summer Flounder</td>
<td>0.721</td>
<td>0.404</td>
<td>0.82</td>
<td>0</td>
</tr>
<tr>
<td>Weakfish</td>
<td>0.694</td>
<td>0.387</td>
<td>0.713</td>
<td>0.407</td>
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After fitting each random forest model, the environmental datasets and random forest models were utilized to predict present and future species distributions using the ‘Predict Random Forest from Rasters’ tool in MGET for ArcMap 10.4.1. Probability of presence was predicted for each species in the three time periods (1958-2010, 2006-2055, 2050-2099) for the spring and the fall. The presence prediction (1958-2010) was subtracted from the future predictions to demonstrate areas of change over time, with positive areas showing an increase in probability of presence and negative areas indicating a decrease in probability of presence. Probability of presence predictions were clipped to only include areas where the original range in salinity and bottom temperature from the trawl dataset occurred. To do this, the minimum and maximum salinity and temperature was identified for the spring and fall dataset. These values were then used to clip the probability of presence rasters for each of the future period by identifying areas that fall within the desired range, and then clipping the raster outputs using a mask. Thus, each spring and fall future period covers a different area, depending on the changes in bottom temperature and salinity (Figure 4).
RESULTS

I. Historical Shifts in the Mean Center of Latitude

Overall shifts in the mean center of latitude can be observed for each species (Figure 5). Atlantic croaker experienced a slight southward shift in the fall, and a slight northward shift in the spring. Atlantic Menhaden observed a slight southward shift in both the fall and spring, with higher variance around the mean. Atlantic spadefish observed a southward shift in both the fall and the spring. Butterfish observed a southward shift in both the fall and the spring. Spot observed little to no shift in the fall and spring. Summer flounder observed little to no shift in the fall and spring. Weakfish observed a northward shift in the fall, and little to no shift in the spring. None of these shifts were statistically significant (p-value <.05).
The historical shifts in mean center of latitude can be compared to the AMO and NAO index as well as the mean SST of the study area in order to understand what is driving certain shifts in the center of latitude. The AMO index has been positive since 1995, while the NAO index has fluctuated over the last 25 years (Figure 6). These fluctuations may influence the historical distributions of these species. In the fall, a positive AMO results in a northward shift in latitude for Atlantic croaker and Weakfish, a southward shift in latitude for Atlantic menhaden, Atlantic spadefish, Butterfish, Spot, and Summer Flounder. The same patterns hold in the spring. The relationship between the AMO and mean center of latitude was statistically significant for Atlantic spadefish in the fall and Summer flounder in the spring and fall (Table 2) (Figure 1A, appendix).

In the fall, a positive NAO is associated with a northward shift in mean center of latitude for Atlantic spadefish and Summer flounder and a southward shift for Atlantic croaker, Atlantic menhaden, Butterfish, Spot, and Weakfish and a northward shift for Atlantic spadefish and Summer Flounder. In the spring, a positive NAO is associated with a northward shift in mean...
center of latitude for Weakfish and a southward shift for Atlantic croaker Atlantic menhaden, Atlantic spadefish, Butterfish, Spot, and Summer Flounder. The relationship between NAO and mean center of latitude was statistically significant for Atlantic menhaden in the spring.

In the fall, a positive winter NAO is associated with a northward shift in the mean center of latitude for Atlantic croaker, Atlantic menhaden, Atlantic spadefish and Summer flounder and a southward shift for Butterfish, Spot and Weakfish. In the Spring a positive winter NAO is associated with a northward shift for Atlantic menhaden, Atlantic spadefish, Butterfish, and Weakfish and a southward shift for Atlantic croaker, Spot, and Summer Flounder. The relationship between NAO and mean center of latitude was not statistically significant for any species.

In the fall, increasing SST is associated with a northward shift for Atlantic menhaden, Atlantic spadefish, Butterfish, and Weakfish and a southward shift for Atlantic croaker, Spot, and Summer flounder. In the fall, increasing SST is associated with a northward shift for Atlantic spadefish, Butterfish, Spot, Summer flounder and Weakfish and a southward shift for Atlantic croaker and Atlantic Menhaden. The relationship between the SST and mean center of latitude was statistically significant for Summer flounder in the fall.

Figure 6. AMO, NAO and Winter NAO index and annual SST over 35-year period between 1990 and 2015.
Table 2. Regression coefficients depicting incremental influence of one unit change in dependent variable

<table>
<thead>
<tr>
<th></th>
<th>Atlantic Croaker</th>
<th>Atlantic Menhaden</th>
<th>Atlantic Spadefish</th>
<th>Butterfish</th>
<th>Spot</th>
<th>Summer Flounder</th>
<th>Weakfish</th>
</tr>
</thead>
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<tr>
<td></td>
<td>Fall</td>
<td>Spring</td>
<td>Fall</td>
<td>Spring</td>
<td>Fall</td>
<td>Spring</td>
<td>Fall</td>
</tr>
<tr>
<td>AMO</td>
<td>0.39</td>
<td>1.06</td>
<td>-0.04</td>
<td>-0.12</td>
<td>-2.43 *</td>
<td>-1.58</td>
<td>-1.85</td>
</tr>
<tr>
<td>NAO</td>
<td>-0.1</td>
<td>-0.10</td>
<td>-0.12</td>
<td>-0.31 *</td>
<td>0.01</td>
<td>-0.04</td>
<td>-0.24</td>
</tr>
<tr>
<td>Winter NAO</td>
<td>0.09</td>
<td>-0.03</td>
<td>0.10</td>
<td>0.15</td>
<td>0.11</td>
<td>0.06</td>
<td>-0.001</td>
</tr>
<tr>
<td>SST</td>
<td>-0.09</td>
<td>-0.12</td>
<td>0.51</td>
<td>-0.12</td>
<td>0.12</td>
<td>0.23</td>
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(P<.05*)

II. Environmental Datasets

The regionally downscaled GCM datasets demonstrate a predicted increase in bottom temperatures throughout the study area in both the spring and fall periods (Figure 7). Bottom temperatures in the study area are projected to increase by an average of 1.08°C from 2006-2055 and by 2.58°C from 2050-2099 in the spring months (April May and June), and by an average of 1.19°C from 2006-2055 and by 2.82°C from 2050-2099 in the fall months (October, November, December) (Table 3).

As noted by Grieve et al (Grieve et al 2016), the influence of the Gulf Stream results in a unique oceanographic climatology along the South Atlantic Bight. An inshore–offshore temperature gradient between the cold, inshore waters and the warmer offshore waters near the Gulf Stream develops during the winter months (DJFM). This thermal gradient reverses the summer months (June to September), resulting in an increase in inshore shallow water temperatures. Although this study was conducted on spring and fall datasets, the same phenomena can be observed. In the spring months (AMJ), the temperature increases inshore, while in the fall (OND) the waters offshore are the warmest (Figure 7).

Table 3. Environmental statistics, showing change in average BT for the two future periods

<table>
<thead>
<tr>
<th></th>
<th>Min</th>
<th>Max</th>
<th>Mean</th>
<th>Stdev</th>
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<tr>
<td>AMJ BT 2006-2055</td>
<td>.864</td>
<td>2.068</td>
<td>1.081</td>
<td>.277</td>
</tr>
<tr>
<td>AMJ BT 2050-2099</td>
<td>2.168</td>
<td>4.655</td>
<td>2.587</td>
<td>.587</td>
</tr>
<tr>
<td>OND BT 2006-2055</td>
<td>.805</td>
<td>2.376</td>
<td>1.197</td>
<td>.378</td>
</tr>
<tr>
<td>OND BT 2050-2099</td>
<td>2.217</td>
<td>5.069</td>
<td>2.823</td>
<td>.679</td>
</tr>
</tbody>
</table>
III. Predicted Future Presence

The following results depict changes in predicted probability of presence for the seven species in the spring and fall. A more detailed look at the variable importance plots and partial dependence plots can be found in the appendix (Figure 2A, Figure 3A).

*Atlantic croaker*

In the fall, Atlantic croaker demonstrated an increase in presence in the inshore areas and a decrease in presence in the offshore and northern areas (Figure 9,10). High probability of presence was associated with intermediate bottom temperatures and with lower salinity levels (Figure 9,10, 3A). Salinity had the highest relative variable importance, with bottom temperature and winter NAO having slightly less relative importance (Figure 2A).
In the spring, Atlantic croaker demonstrated an increase in presence in inshore areas and northern areas and a decrease in presence in offshore southern areas (Figure 11,12). High probability of presence was associated with warmer waters and higher salinity. Salinity had the highest variable importance, with NAO having the next highest.

**Atlantic menhaden**

In the fall, Atlantic menhaden demonstrated an increase in probability of presence in offshore and northern areas and a decrease in probability of presence near shore. These shifts were not as high in magnitude as other species (Figure 9,10). There was little to no association of probability of presence with changes in bottom temperature or salinity, and the climate variations had the highest variable importance, with salinity and bottom temperature having little variable importance.

In the spring, Atlantic menhaden demonstrated an increase in presence in inshore and northern waters and a decrease in presence in offshore waters (Figure 11,12). High probability of presence was associated with lower bottom temperatures and higher salinities. Salinity and substrate had the highest relative variable importance for predicting probability of presence.

**Atlantic spadefish**

In the fall, Atlantic spadefish demonstrated an increase in presence in offshore southern waters and a decrease in presence in inshore southern and all northern waters (Figure 9,10). High probability of presence was associated with higher bottom temperatures, and lower salinity. Salinity and bottom temperature had the highest relative variable importance, with salinity having the highest.

In the spring, Atlantic spadefish demonstrated an increase in presence in inshore southern waters and a decrease in presence in offshore southern waters and northern waters (Figures 11,12). High probability of presence was associated with higher salinities, and there was little to no relationship between bottom temperature and probability of presence. Salinity had the highest relative variable importance.

**Butterfish**

In the fall, Butterfish demonstrated an increase in presence in northern waters and inshore
southern waters. High probability of presence was associated with cooler bottom temperatures and lower salinities (Figure 9,10). The climate variations had the highest relative variable importance and salinity and bottom temperature had similar relative variable importance.

In the spring, Butterfish demonstrated an increase in presence in northern and inshore waters and a decrease in presence in offshore waters (Figure 11,12). High probability of presence was associated with high bottom temperature and high salinity. Salinity had the highest relative variable importance with bottom temperature having the next highest relative importance.

**Spot**

In the fall, Spot demonstrated a decrease in probability of presence in offshore southern waters and an increase in northern waters and some inshore southern waters (Figure 9,10). High probability of presence was associated with all bottom temperatures and lower salinity. Salinity had the highest relative variable importance with NAO having the second highest.

In the spring, Spot demonstrated an increase in some northern waters, but overall a decrease in presence was observed for most of the study area (Figure 11,12). High probability of presence was associated with all bottom temperatures and with high salinities. Salinity had the highest relative variable importance.

**Summer Flounder**

In the fall, Summer flounder demonstrated an increase in presence in inshore southern waters and offshore northern waters and a decrease in presence in inshore northern waters and offshore southern waters (Figure 9,10). High probability of presence was associated with intermediate and low bottom temperatures and lower salinities. Bottom temperature had the highest relative variable importance with salinity having a close relative variable importance.

In the spring, Summer flounder demonstrated an increase in presence in offshore southern and northern waters and a decrease in presence in inshore southern waters (Figure 11,12). High probability of presence was associated with high bottom temperatures and lower salinities. Salinity had the highest relative variable importance with bottom temperature having the next highest.

**Weakfish**
In the fall, Weakfish demonstrated an increase in presence in some offshore southern waters and northern waters, and a decrease in presence in southern waters and the waters around Cape Hatteras (Figure 9, 10). High probability of presence was associated with all bottom temperatures, and lower salinities. Salinity had the highest relative importance with bottom temperature having the next highest.

In the spring, Weakfish demonstrated an increase in presence in southern inshore waters and northern waters and a decrease in presence in offshore southern waters (Figure 11, 12). High probability of presence was associated with high bottom temperatures and salinities. Salinity had the highest relative importance with NAO having the next highest.

**Figure 8.** Example of variable importance plot and partial dependence plots as shown in Figures 9-12
Figure 9. Change in probability of presence for fall species calculated by subtracting 2006-2055 predictions from present predictions.
Figure 10. Change in probability of presence for fall species calculated by subtracting 2050-2099 predictions from present predictions.
Figure 11. Change in probability of presence for spring species calculated by subtracting 2006-2055 predictions from present predictions.
Figure 12. Change in probability of presence for spring species calculated by subtracting 2050-2099 predictions from present predictions.
DISCUSSION

The aim of this research was to understand historical shifts of commercially managed species as they are related to anthropogenic warming and natural climate variations and to explore the potential for distribution shifts of several commercially managed marine fish species under a particular climate change scenario. In general, no two species behaved exactly the same, and it is important to consider the unique life-histories of each species when calculating expected distribution shifts. Based on the above analysis, we have developed five main conclusions on the relationship between the seven studied species and anthropogenic global warming: (1) both natural climate variations and sea surface temperatures influence the historical mean latitude of several species; (2) differing oceanographic conditions in the Mid Atlantic Bight and South Atlantic Bight lead to different projected future species distributions; (3) future shifts in probability of presence vary in intensity and direction depending on the season, location, and importance of environmental variables for the species; (4) projected shifts may influence seasonal migrations for some species; (5) salinity is largely important for predicting species distributions.

I. The importance of Climate Variables

When examining potential future shifts in species distributions, it is important to examine the overall influence of natural climate variations and SST on historical shifts in presence in order to appropriately attribute the relative influence of anthropogenic climate change versus naturally occurring climate variations. To examine the influence of natural variations on the presence of each species, we examined the incremental influence of positive and negative NAO and AMO values on the mean center of latitude. Additionally, the relative importance of NAO and AMO values were calculated in the variable importance measures, as a result of the random forest model. Several noteworthy trends were identified.

Of the climate variables, AMO had the highest predictive power for mean center of latitude, indicating that the recent positive trend may result in the observed latitudinal shifts of several species. Atlantic spadefish (fall) demonstrated a relationship between change in mean center of latitude and AMO, with a positive AMO associated with a southward shift in the center of latitude for this species in the fall. The recent positive AMO for the last 20 years is most likely driving the southward shift in this species. The importance of the AMO can also be observed for
Summer Flounder in the fall and spring, where a positive AMO is significantly correlated with a decrease in latitude, or a southward shift. Sea surface temperature was also significantly correlated with a southward shift for Summer flounder (fall), suggesting that the species responds to both the AMO and increasing SST (Table 2). When observing the variable importance plots for these species it is evident that bottom temperature and salinity have higher relative importances than the climate variations for both Atlantic spadefish in the fall, and Summer flounder in the spring and fall. Thus, when examining the future distributions of these species it would be important to consider projected changes in the AMO as well as ocean warming.

II. Different oceanographic conditions in SAB and MAB

Previous research suggests ocean warming will drive species to search for cooler waters, which will cause them to shift offshore and poleward. Although, several species have shifted offshore in our analysis, it is mostly in search of warmer waters near the gulf stream. Thus, it is important to consider the unique oceanography of the South Atlantic Bight and Mid Atlantic Bight when considering species distribution shifts. Due to the nearness of the Gulf Stream, bottom temperature is higher offshore in the fall and inshore in the spring (Atkinson et al, 1983) (Figure 7). The varying temperature gradient in the spring and fall will lead to different projected presence for a several studied species, such as Summer flounder.

Additionally, in the fall, the future Mid Atlantic Bight waters experienced greater increases in temperature as compared to the South Atlantic Bight areas and the Mid Atlantic Bight waters began to mirror the present-day South Atlantic Bight waters. In the spring there was not as noticeable of an increase in the Mid Atlantic Bight water temperature as was observed in the fall (Figure 3). These higher increases in Mid Atlantic Bight waters in the fall lead to increased probability of presence for a variety of species in those areas in the fall and not as much in the spring (Figure 10; Butterfish, Spot). Additionally, increased warming in the fall allows the northern waters to come within the range of the dataset, and therefore, within the range of the predicted presence.

Furthermore, salinity gradients are different in the South Atlantic Bight and Mid Atlantic Bight waters (Figure 3). In both the fall and the spring, high salinity is found very nearshore in South Atlantic Bight waters up to North Carolina. Once past North Carolina, however, the high
salinity levels are much farther offshore, and the inshore Mid Atlantic Bight waters are
dominated by lower salinity waters. As salinity increases in the future climate models, the Mid
Atlantic Bight waters experience similar salinities to the South Atlantic Bight present conditions,
but the varying gradients still exist. The influence of the salinity gradient can be observed in
many species, as salinity was one of the most important predictor variables throughout. Several
species observed an increased probability of presence inshore in the South Atlantic (Atlantic
croaker Spring, Atlantic spadefish Spring, and Summer flounder Fall) and increased probability
of presence offshore in the Mid Atlantic (Summer flounder Fall), which is most likely a direct
result of the varying salinity gradient between the Mid Atlantic and South Atlantic Bight
(Figures 9-12).

These results may prove useful for future studies. Not only is it important to consider areas of
high changes in bottom temperature (inshore) and salinity (inshore and offshore), but it is also
important to consider the areas where bottom temperatures (offshore fall, inshore spring) and
salinities (offshore) will increase beyond the preferred tolerance of many species. Perhaps
present day South Atlantic Bight waters could represent a look into the future for the Mid
Atlantic areas.

III. Varying importance of environmental variables

For each of the seven species modeled, the environmental variables (salinity and bottom
temperature) had varying relative importance when compared to the natural climate variations.
These variances in importance are also reflected in the predicted future distributions of the
species. In the fall, Atlantic menhaden demonstrated high variable importance for the climate
indices and low variable importance for both salinity and bottom temperature. As a result, the
predicted changes in presence are minimal, as noted by the light yellow and green in Figure 10.
On the contrary, Atlantic croaker, Atlantic spadefish, and Summer flounder demonstrated higher
variable importance for bottom temperature and salinity (as opposed to the climate indices), and
thus their predicted gains and losses in presence are much more pronounced (Figure 10).

These results can have implications for management. Atlantic menhaden are a highly
migratory species, which may suggest they can tolerate a large range of temperatures and
salinities. By combining their known life-history with our results, we conclude that Atlantic
menhaden are not as vulnerable to changes in bottom temperatures and salinities as the other
species. Atlantic spadefish are known to inhibit waters from North Carolina to the Bermuda and the Gulf of Mexico (Bell et al 2005). Our fall results indicate that predicted presence increases with increasing temperatures, but decreases with increasing salinity. As salinity is the stronger predictor variable, we will expect to see increases in the offshore waters, where salinity does not increase as dramatically. Bottom temperature will still play a role in the abundance of this species, and Atlantic spadefish presence will increase in areas where bottom temperature tends to increase to their preferred warm temperatures. In this case, the areas offshore near the Gulf Stream will be within Atlantic spadefish’s preferred warm temperatures.

IV. Influence on known seasonal migrations

Several of the studied species are known to migrate inshore and offshore depending on the season. Summer Flounder, for example, are known to occupy cooler waters from Cape Hatteras, North Carolina to Cape Cod, Massachusetts, and they generally move offshore in the fall to spawn and return inshore for the spring and summer (Packer et al 1999). Our results indicate summer flounder are decreasing in presence offshore in the fall (Figure 10) and inshore in the spring (Figure 12). In the fall, bottom temperature is the most important predictor variable, and Summer flounder prefer intermediate bottom temperatures. Due to the offshore temperature gradient, waters in the fall are much warmer offshore near the gulf stream, and the inshore areas remain intermediate. Thus, Summer Flounder are forced to increasingly occupy the inshore waters off the coast of North and South Carolina. In the spring, salinity is the most important predictor variable for Summer flounder presence, which decreases with increased salinity. As the inshore areas increase much more in salinity, Summer flounder will shift further offshore.

Given the modeled results, in the future, Summer flounder annual migrations may face unexpected challenges in relation to increasing inshore salinity in the spring and offshore bottom temperature in the fall. Given the importance of annual migrations for the species, it is imperative that management consider these implications for the survival of the stock.

V. Importance of salinity

For each of the seven species modeled, salinity had the highest variable importance for four species in the fall and all species in the spring. Of the fall models, only one (Summer Flounder) had bottom temperature as the most important variable. In the fall, Atlantic menhaden, Butterfish
and Spot had the NAO as the most important variable, followed by salinity. The importance of salinity must be considered when determining future management of these seven species. Salinity increased in nearshore waters (within the studied range) and in offshore waters (outside of the studied range). As salinity increases more in the inshore areas in the South Atlantic in the spring and fall, species may be forced to occupy smaller and smaller ranges. Species such as Atlantic spadefish in the fall, that prefer the low intermediate salinities will occupy a small strip of waters offshore as those areas experience the least amount of increases in salinity (Figure 10).

VI. Limitations

It is important to identify the limitations of the approaches used in this study. This study examined the role of bottom temperature, salinity, habitat, and natural climate variations on species distribution abundances, but was unable to examine the potential effects of fishing pressure on species distributions and abundance. Additionally, as with any predictive study, this study made several key assumptions. First, we assumed that the behavior of each species will not change going into the future, which does not consider the ability of certain species to adapt to environmental changes. Additionally, we focused on long-term climatological changes resulting from anthropogenic ocean warming and used a 50-year average of ocean conditions. This limited the noise in modeled temperatures that can be associated with inter-annual variation. Consequently, this analysis projects where each species could be found, but not precisely where and when they will be found. Furthermore, we focused on the RCP 8.5 climate change scenario, which is considered the ‘business as usual scenario’ and anticipates increasing rates of emissions over time. Although, during the last five years, emissions have met or surpassed the RCP 8.5 scenario (Fuss et al 2014), it is still difficult to accurately predict the exact amount of future emissions. Despite these limitations, we anticipate our results will be valuable for fisheries managers as they anticipate the likelihood of species distribution shifts in their management areas.

CONCLUSION

In general, the Mid Atlantic and South Atlantic Bight are expected to experience increased ocean warming and salinity levels in the near future as a result of anthropogenic climate change.
Consequently, species will shift distributions depending on their preferred temperature and salinity range, the season, and the importance of environmental variables on their distribution. Species with temperature and salinity as an important predictor variable experience greater projected distribution gains and losses in future periods. For some species, projected shifts could negatively affect their seasonal migrations, while others may show little changes in projected distributions. Ultimately, understanding the influence of bottom temperature and salinity as well as naturally occurring climate variations will help to predict future distributions by attributing the likely causes of species shifts.

Most of the previous research to identify changes in species distributions in response to anthropogenic climate has emphasized the potential for northward and offshore shifts. This study identified several species that will shift inshore and increase in southern areas. The difference between previous research, and these predictions is largely a result of the regional scale of this analysis and the preferences of the species studied. Our results highlight the importance of running future distribution models at regional scales, for the observed impacts of climate change on the South Atlantic species varies from the trends identified in other analyses. While, globally, many species will shift poleward and deeper, applying this expectation while ignoring the unique oceanographic features of the study area may lead to faulty predictions.

The predictive power of bottom temperature and the species thermal tolerance should be considered when projecting future species distributions in a warming climate. This study demonstrates the importance of climate and fisheries research in the Mid-Atlantic and South-Atlantic Bight and emphasizes need for future research on the magnitude and direction of future species distributions. Although modeling future projections encourages uncertainty, steps must be taken to hypothesize future distribution shifts before they happen, giving management adequate time to respond.

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APPENDIX
Figure 1A. Regression results for mean center of latitude related to annual AMO, NAO, winter NAO and Annual SST.
Butterfish Fall

Butterfish Spring

Spot Fall

Spot Spring

Flounder Fall

Flounder Spring
Figure 2A. Variable importance plots obtained from Random Forest Analysis
Figure 2A. Partial Dependence plots obtained from Random Forest Analysis