EXPANDING MARINE FISH AND INVERTEBRATE SPECIES DISTRIBUTION MODEL PROJECTIONS INTO THE SOUTHERN BAY OF FUNDY AND NOVA SCOTIA

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Executive Summary

1. **Southern Bay of Fundy and Nova Scotia waters are expected to continue warming under future climate scenarios.**
   - Global climate model ensembles run under two representative concentration pathway scenarios (RCP4.5 and RCP8.5), suggest sea surface temperatures within the southern Bay of Fundy/Nova Scotia regions will continue increasing at comparable rates to the Northeast Shelf U.S Large Marine Ecosystem.
   - Sea surface temperature projection differences become apparent around mid-century (2055) and result in unique annual warming rates over the time period of 1982-2100 (RCP4.5 ~ 0.025°C/year versus RCP8.5 ~ 0.045°C/year).
2. **Climate-driven warming will result in changes in the distribution and abundance of marine species within southern Bay of Fundy and Nova Scotia waters.**
   - Across the southern Bay of Fundy/Nova Scotia region, species distribution model projections for focal species suggest:
     - Declines in the relative biomass of American lobster;
     - Declines in the relative biomass of Atlantic herring and Atlantic cod in the fall, with no major change in the spring;
     - No major changes in relative biomass of sea scallop in either season;
     - Increases in relative biomass of longfin squid, summer flounder and black sea bass in both seasons.
   - Model projections for the Nova Scotia region should be considered carefully as this region is outside the surveyed area and are provided for demonstration.
3. **Scenarios of future species changes can support forward-looking climate adaptation planning efforts.**
   - Results provide one scenario of future species availability, which can be used as a foundation for 'what if?' community conversations about climate vulnerabilities and adaptation strategies.
   - Further analysis and investigation will be needed to better answer socio-ecological questions and assess adaptation strategies. For example, will increases in emerging species translate into fishing opportunities?
4. **Promising opportunities to advance modeling efforts can draw upon new approaches and include data from Canadian fisheries surveys.**
   - While historical observations have commonly been used to guide decision making processes, this approach is problematic as climate change reduces the reliability of past conditions as good indicators of the future.
   - Novel distribution modeling approaches, which account for environmental variables as well as unmeasured biological processes and species interactions, may provide more accurate projections of species distribution and abundance.
   - Coupling new modeling approaches with Canadian fisheries survey data could provide an incredible opportunity to advance our understanding of how climate change will impact marine species in the region and better support the ability of stakeholders to make sustainable, climate-smart decisions.

Overview

Species distributions are shifting in response to warming ocean temperatures, triggering complex ecological, conservation and management challenges. As species that have traditionally been important to fisheries move or decline, social and economic impacts are felt in fisheries, fishing industries, and coastal communities. Conversely, other species may become more prevalent, creating potential new opportunities for fishermen and shoreside businesses. Understanding projected future species distribution changes provides foundational insights into potential climate impacts, vulnerabilities, and adaptation strategies for fisheries and communities.

Traditionally, fishermen have been able to rely on an intuition developed over years of past observations to anticipate likely future trajectories of species they fish. However, climate change is making this approach increasingly problematic, as historical observations may no longer be good indicators of upcoming conditions (Milly et al. 2008; Craig 2010; Dietze et al. 2018). To make sustainable and responsible decisions within this dynamic environment, we need models with the ability to accurately describe observed patterns and project the future distribution and abundance of marine fish species.

Species distribution models are one of the most popular tools for meeting this information need and for describing, understanding, and projecting species distributions under future climate scenarios (Guisan and Zimmermann 2000; Hazen et al. 2013; Payne et al. 2016). Given their importance in providing forward-looking information, there have been numerous approaches developed and applied to a wide array of species, including marine species within the Northeast Shelf U.S. Large Marine Ecosystem (e.g., Allyn, A. J. et al. In press; Kleisner et al. 2017; Morley et al. 2018; Rogers et al. 2019) and on the Scotian Shelf (Shackell et al. 2014, Stortini et al. 2015). However, the Canadian studies to date have focused on species that were already found in the Gulf of Maine or Scotian Shelf. As water temperatures are rising in the region, whether species that are traditionally found south of Cape Cod will move into Bay of Fundy and Scotian Shelf waters is becoming of interest.

Goal and Objectives

Our goal was to expand our current modeling efforts of marine fish and invertebrates along the Northeast U. S. Shelf into the southern Bay of Fundy and Nova Scotia as a way of providing information to Eastern Charlotte Waterways about expected changes in species distribution and abundance within these regions under future climate conditions. To reach this goal, we had the following objectives:

(1) Collect NOAA Northeast Fisheries Science Center (NOAA NEFSC) seasonal bottom trawl survey data from 1982-2018 spanning the entire survey region, including tows made in waters near the Bay of Fundy and Nova Scotia;
(2) Collect global climate model sea surface temperature (SST) projections run under the representative concentration pathway (RCP) 4.5 and 8.5 scenarios and explore projected temperature trends within the U.S. Gulf of Maine, Bay of Fundy and Scotian Shelf regions;

(3) Fit and validate two-stage delta log normal distribution models using NOAA NEFSC bottom trawl survey data from 1982-2012 for training models and 2013-2018 for testing fitted models;
(4) Use fitted models to project species probability of presence and relative biomass in the southern Bay of Fundy and Nova Scotia waters using expected temperatures from an ensemble of climate models run using RCP 8.5 “business as usual” scenario;
(5) Synthesize model projections into maps, graphs and tables for distribution and use by the Eastern Charlotte Waterways organization.

Methods

Overview

In an effort to support reproducing this work and being transparent about the methods used and analysis steps taken, we have provided our code on GitHub, which can be accessed here https://github.com/aallyn/ECW_FishClimate. To run the code, please contact Andrew Allyn (aallyn@gmri.org) and he will be able to provide all of the necessary data files, which were not uploaded given GitHub file restrictions.

Data Collection

Biological Data

In this study, we used species biomass data from spring and fall bottom trawl surveys conducted since 1968 by the NOAA Northeast Fisheries Science Center (NEFSC) (Azarovitz 1981; Politis et al. 2014). These surveys cover an area from Cape Hatteras, North Carolina to the Gulf of Maine, including Georges Bank and the Bay of Fundy (Fig. 1). A stratified random sampling design divides the region into strata based on depth, bottom habitat type and latitude. During a given survey, stations are randomly selected within each stratum proportional to the stratum area, with a minimum of two successful stations required in each stratum (Politis et al. 2014). At each station, a bottom trawl net is towed along consistent depth contours for a set time and speed. The catch is then sorted to species, counted and weighed. For our analysis, we then only included data from representative tows (i.e., consistent durations, no major gear problems) and for species that were included in a recent climate vulnerability assessment within the region (Hare et al. 2016).

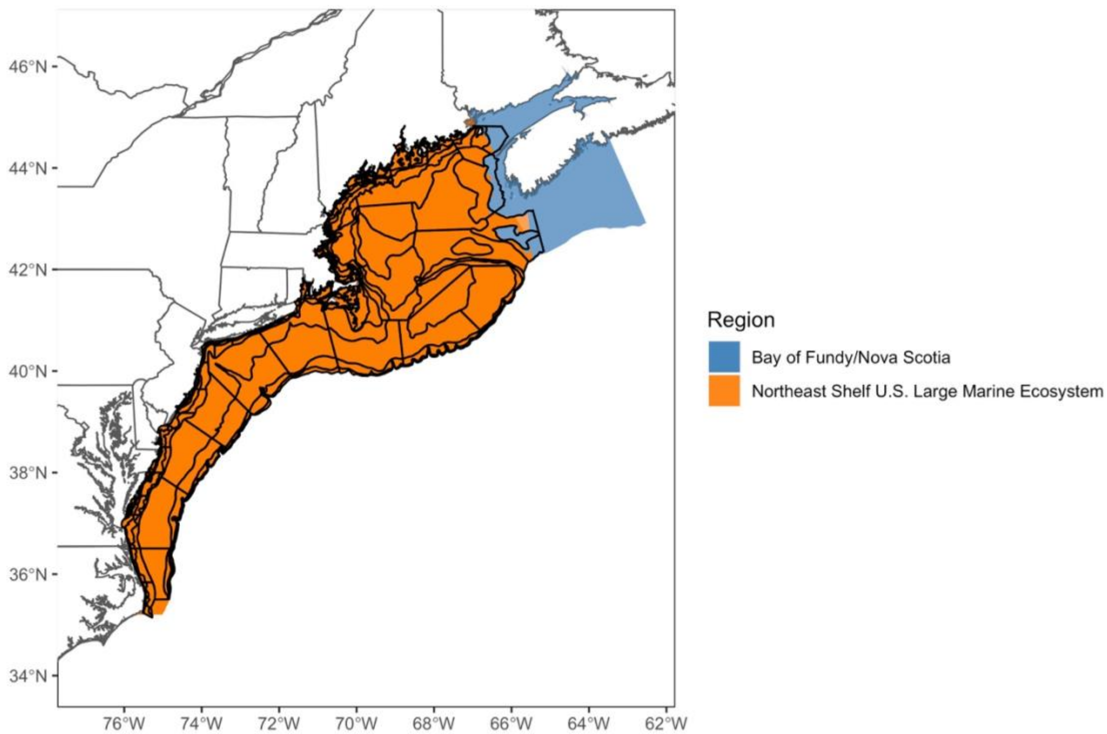

Figure 1. The study region, including the Northeast Shelf U.S. Large Marine Ecosystem and Bay of Fundy/Nova Scotian waters, along with NOAA Northeast Fisheries Science Center spring and fall bottom trawl strata (black lines). As indicated by this map, and discussed below in the species projection methods, we provide species projections for the entire study region as a pilot effort, including waters outside the boundaries of the NOAA Northeast Fisheries Science Center survey.

Historical Environmental Data

We used depth and seasonal sea surface temperature (SST) to characterize local ecosystem conditions, as they are well known to influence the distribution and abundance of marine fish and invertebrates. Depth data were downloaded from the NOAA ETOPO1 Global Relief Model (Amante and Eakins 2009), which integrates topographic elevation measurements and ocean bathymetric measurements with a 1 arc-minute resolution. The depth at specific tow locations was extracted using bilinear interpolation of depth values from four neighboring cells with the R raster package v3.0-7 (Hijmans 2019). Daily SST data were gathered from the NOAA Optimum Interpolation Sea Surface Temperature (OISST) dataset, with a spatial resolution of 0.25 degrees (Reynolds et al. 2007; Banzon et al. 2016). We first collected the full OISST time series, which spanned from 1982 to present, at each of the tow locations and then averaged daily temperature records over a season. For tows completed during the spring, we averaged all SST values between March and May, and for tows in the fall we averaged SST values between September and November. These months span the time when each seasonal survey was completed.

Projected Sea Surface Temperatures

We downloaded outputs from the CMIP5 ensemble of climate models through the Department of Energy Lawrence Livermore National Laboratory ESGF data node. We used the Climate Data Operators (https://code.mpimet.mpg.de/projects/cdo) toolbox to (1) remap each of the climate model projections to a standard 1 x 1 deg latitude x longitude grid, (2) mask values over land or in the Great Lakes, and (3) crop the extent of the climate model projections to a region of interest.

From these model outputs, we estimated future SSTs. For each of the model members, we first calculated a baseline monthly climatology by averaging estimated temperatures at each grid cell for each month from 1982 through 2011. We then calculated year-month temperature anomalies for 1982-2055 from the 1982-2011 climate model ensemble member's climatology. After calculating these anomalies, we added them to a 1982-2011 climatology calculated from the observed OISST data. This process yielded downscaled year-month temperature estimates from 1982 to 2055, where the resolution of the downscaled estimates matched the resolution of the OISST data (0.25 degree grid cells). Adding the anomalies to the observed OISST climatology rather than the climatology from the ensemble member helped account for a "warm bias" that tends to occur in Northwest Atlantic ocean water temperatures due to the position of the Gulf Stream in many models (Wang et al. 2014; Saba et al. 2016). After removing the warm bias, we determined the monthly ensemble mean, 5th (second coldest model temperature) and 95th (second warmest model temperature) percentiles using estimated temperatures from the ensemble members. Finally, we calculated 2055 fall and spring seasonal average temperatures for each grid cell by averaging March, April and May temperatures for spring and September, October and November temperatures for fall.

Data Analysis

Model fitting

To describe and project marine fish and invertebrate species distribution and abundance, we fit a two-stage delta log normal generalized additive model (GAM). This modeling approach has been widely used in other marine fish distribution modeling studies (Allyn, A. J. et al. In press; Pinsky et al. 2013; Kleisner et al. 2017; Morley et al. 2018) and has several advantages. First, the two stage approach models presence/absence and then models the log positive biomass observations (Lo et al. 1992; Stefansson 1996; Maunder and Punt 2004), so this structure accommodates situations where the number of absence observations exceeds those expected from traditional "count" distributions. Second, the additive modeling framework requires no a priori assumptions about the functional relationships between the response (species presence/absence and biomass) and predictor variables, allowing for non-linear relationships (Wood 2017, 2019; Pedersen et al. 2019).

For each species, we fit seasonal delta log-normal GAMs with the gam function in the R mgcv package v1.8-29 (Wood 2019). We used penalized cubic regression splines for depth and SST smooth terms and a default of 10 knots. Additionally, we used the function's built in "select" option to remove depth or temperature variables if they had no influence on either the presence/absence or logged positive biomass response.

Model evaluation and validation

We fitted models to training data from 1982-2012 and then evaluated and validated models to testing data from 2013-2018. For model evaluation (i.e., measures of model fit to training data), we calculated the deviance explained for both stages of the two-stage delta generalized additive model. While model evaluation is important, ultimately, we are interested in calculating model validation statistics to assess the predictive performance of models using data not used in the model fitting process. As a first step, we calculated the area under the receiver operating curve (AUC) statistic for the presence/absence model stage. The AUC statistic is a measure of a model's classification ability and determines whether testing data presences correspond with higher predicted probabilities than testing data absences. As such, AUC is only concerned with relative model predicted probabilities (Pearce and Ferrier 2000). To provide a more rigorous assessment of model prediction accuracy that incorporates the actual predicted values, we also proceeded to calculate model statistics that focused more specifically on how well calibrated the models were (i.e., if a model predicts a 0.25 probability of presence, does that really mean a 25% chance of encountering the species). These calibration statistics included the correlation between model predictions and observations, the model predictions centered root mean square error (RMSE), and the ratio between the standard deviation of model predictions to the standard deviation of observations. In combination, these statistics provide insight into the agreement between model predictions and observations (correlation coefficient and RMSE) as well as if the model is producing predictions that exhibit similar spatial variability as observational data (standard deviation ratios) (Taylor 2001).

Projected changes in species distribution and abundance

To project species distribution and biomass to spring and fall 2055, we used mean, 5^{th} and 95^{th} percentile SSTs from the RCP 8.5 scenario applied to the CMIP5 climate model ensemble. Projections were first made with the presence/absence model and then the logged positive biomass model. We then calculated the overall relative biomass by multiplying the projected probability of presence by the exponentiated log positive biomass projections. After making these projections, we explored changes within the entire study area, as well as within just the southern Bay of Fundy and Nova Scotia waters at depths less than 400 m. We selected this depth cut off because less than 1% of samples collected by the NOAA NEFSC, and therefore used to train the models, were collected from waters deeper than 400 m. While we provide species projections for the Scotian Shelf waters, these projections are extrapolations into waters not sampled by the NOAA NEFSC spring and fall bottom trawl survey. We present them mainly as a demonstration to show what would be possible by including Canadian fisheries survey data in those regions.

Results

Projected sea surface temperatures within the southern Bay of Fundy and Scotian Shelf regions

The Bay of Fundy and Scotian Shelf waters have been warming during the historical record (i.e., 1982-present) and are expected to continue warming under future climate scenarios (Fig. 2). The warming rates within the Bay of Fundy and Scotian Shelf regions are similar to neighboring Gulf of Maine region warming rates, with projected increases of 0.048, 0.05, and 0.042^{o}C per year during the 1982-2100 period for the Gulf of Maine, Bay of Fundy and Scotian Shelf regions, respectively, under the RCP 8.5 "business as usual" scenario. Sea surface temperature warming rates are slower for the RCP 4.5 scenario, but still consistent across the three spatial regions (Gulf of Maine = 0.029^{o}C/year, Bay of Fundy = 0.022^{o}C/year and Scotian

Shelf 0.028°C/year). Divergence of sea surface temperature trajectories occurs around mid-century for all three regions.

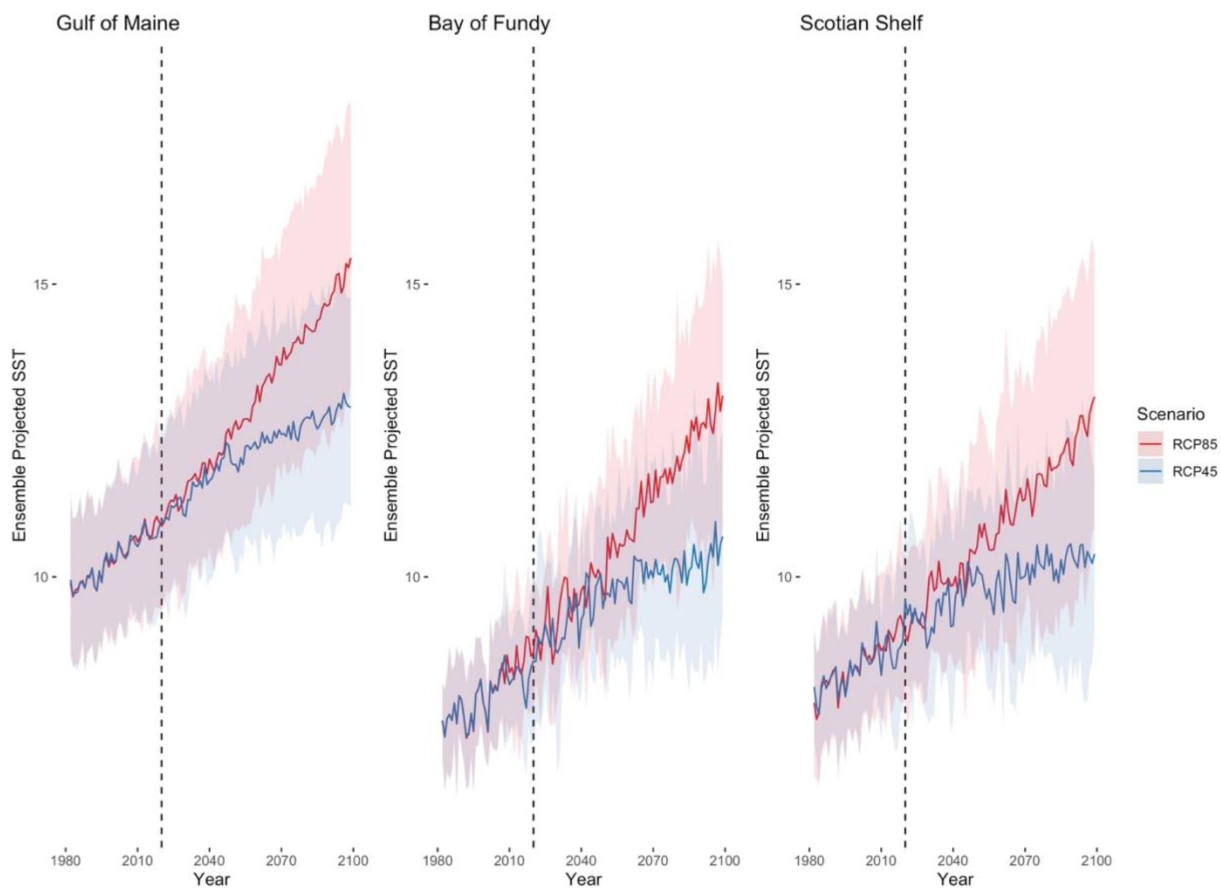

Figure 2. Hindcasted and projected sea surface temperature anomalies for the Gulf of Maine, Bay of Fundy and Scotian Shelf regions for the period of 1982-2100. The projected sea surface temperature anomalies are calculated using the CMIP5 ensemble of climate models for the RCP 8.5 and RCP 4.5 scenarios. Average yearly projected sea surface temperatures are shown (mean = solid lines, shaded region = 5th and 95th percentiles), as well as a dashed line indicating the current year (2020).

Projected distribution and abundance changes of focal species within the southern Bay of Fundy and Scotian Shelf regions

Model validation

Using the 2013-2018 hold out testing data, we were able to rigorously validate the predictive skill of the fitted distribution models. This validation reveals a few key points. First, we are able to fit seasonal models that do a good job for many species of capturing relative habitat use patterns measured by the presence/absence of species relative to the predicted probability of presence for the presence-absence stage of the two-stage delta generalized additive model. For example, the average correlation coefficient across species-seasons was 0.47 and the average AUC was 0.88, indicating models had very good classification skill. However, the models were not as able to predict raw biomass (e.g., kilograms per tow). Model statistics showed that while some models had adequate correlation between predictions and testing data observations, they also had high RMSE values and exhibited considerable bias in matching the variability exhibited in the testing data observations (i.e., model predictions were more smooth than we would expect given the observations). Newer modeling approaches that we have begun implementing would improve the model skill and provide an avenue for incorporating data from Canadian fisheries surveys into the analysis. In summary, we feel confident that models are able to capture relative distribution and abundance patterns, as well as changes in these parameters, but there is much work to be done still to have confidence in the ability of a species distribution model to accurately predict biomass on the raw scale or match the very patchy nature of marine fish and invertebrate distributions.

Projected changes in species distribution and abundance

Warming sea surface temperatures in the southern Bay of Fundy and Nova Scotia waters are likely to cause changes in the distribution and abundance of many marine fish and invertebrate species. Results showing comparisons within different regions across the mean, 5%, and 95% SST projections of the RCP 8.5 scenario are supplied in the "Species distribution and abundance projections" results folder (NELMESpring, NELMEFall, CASpring and CAFall). Focusing on results from the mean projected temperatures of the RCP8.5 climate ensemble and for the fall season (typically models had more predictive skill for the fall season), we see some interesting patterns emerging for species of economic and ecological importance (Fig. 3). Specifically, model projections show declines in all of the groundfish species, expect offshore hake, for both the Northeast Shelf U.S. Large Marine Ecosystem, as well as the southern Bay of Fundy/Nova Scotia region. Similarly, model projections suggest slight declines in the relative biomass of American lobster under continued ocean warming. Although, declines are likely to be more dramatic for the Northeast U.S. Shelf Large Marine Ecosystem than the southern Bay of Fundy/Nova Scotia region. Given its economic and ecological importance, model projected declines for fall biomass of Atlantic herring stand out in the pelagic fish group. In contrast, the relative biomass of some other pelagic species, like butterfish and longfin squid, are expected to increase. These species and other coastal species that are projected to increase (e.g., summer flounder, black sea bass, spot), are currently associated with the warmer waters of the Northeast U.S. Shelf Large Marine Ecosystem around southern New England and the mid-Atlantic Bight. Importantly, some of these fall seasonal patterns do change when looking at the spring season. For example, within the Bay of Fundy/Nova Scotia region, Acadian redfish, American plaice, Atlantic hagfish, ocean pout, red hake, silver hake, witch flounder and yellowtail flounder are expected to have slight to moderate increases in spring relative biomass (see "Species distribution and abundance projections" results folder, NELMEvsCAspring.jpg figure).

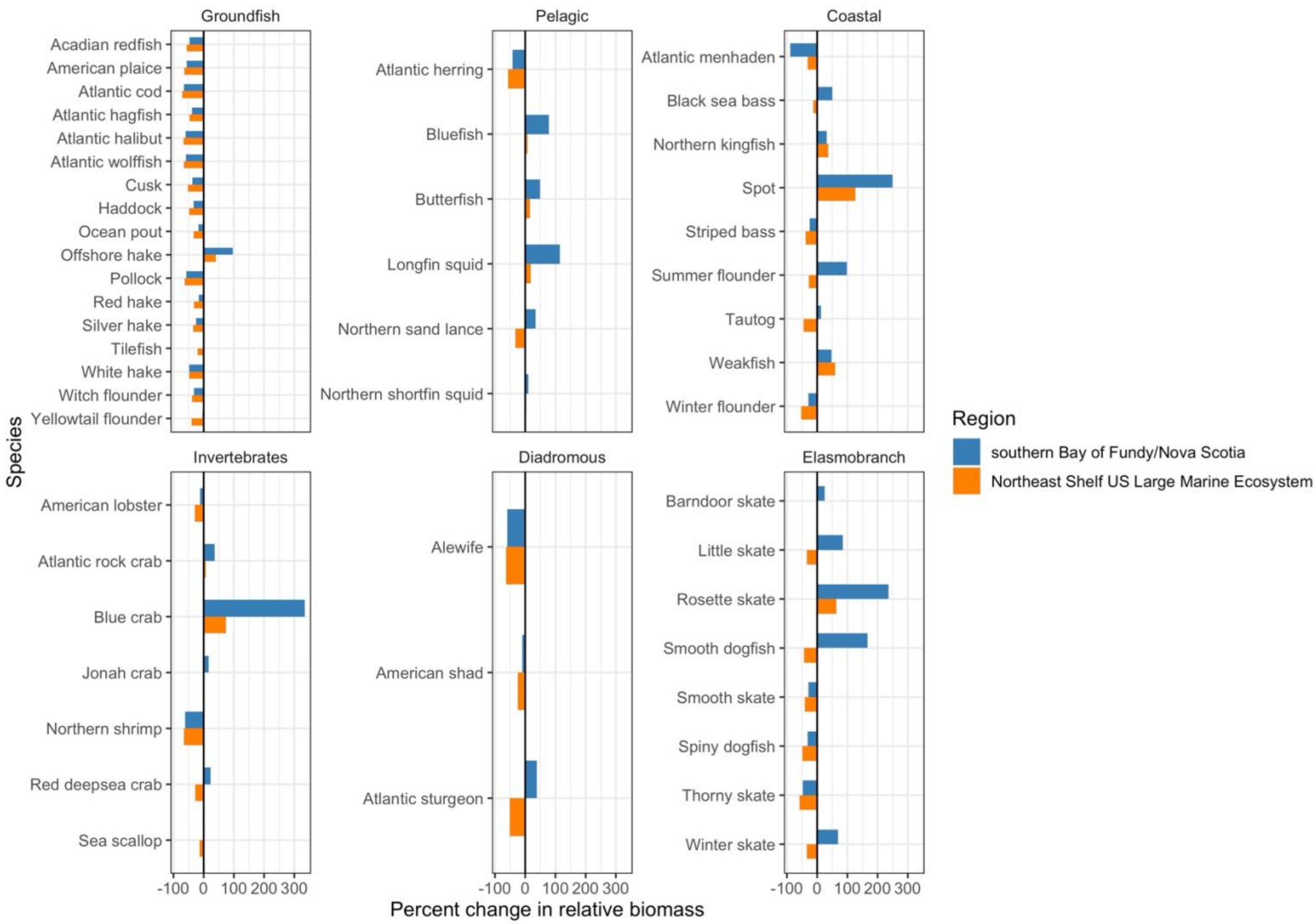

Figure 3. Fall regional projected percent changes in relative biomass by species functional group for the southern Bay of Fundy/Nova Scotia region (blue bars) and the Northeast Shelf U.S. Large Marine Ecosystem region (orange bars). Projections are shown only for species with models that had at least at least reasonable classification ability (AUC >= 0.675) in both the fall and spring seasons and using only the mean CMIP5 RCP 8.5 climate model ensemble projected sea surface temperatures.

Along with the perspective of broad-scale changes in distribution and abundance provided by these regional comparisons, there is also interest in understanding finer-scale patterns within regional boundaries. To that end, seasonal maps of species distribution model predictions for the baseline period (2013-2018) and projected changes under mean projected temperatures of the RCP8.5 scenario are provided for a suite of focal species, including American lobster, Atlantic cod, Atlantic herring, longfin squid, summer flounder, sea scallop and black sea bass (See Species ProjectedBioChanges.tiff files in “Species distribution and abundance projections” results folder). These fine scale maps provide information that is likely going to be more informative for coastal communities and resource managers as they provide a better picture of where changes are expected. For instance, with American lobster (Fig. 4), there is considerable spatial variability in projected biomass changes, especially during the fall season and some areas are expected to decline (e.g., southwest Gulf of Maine/Georges Bank), while other areas like the southern Bay of Fundy may see slight increases in lobster biomass.

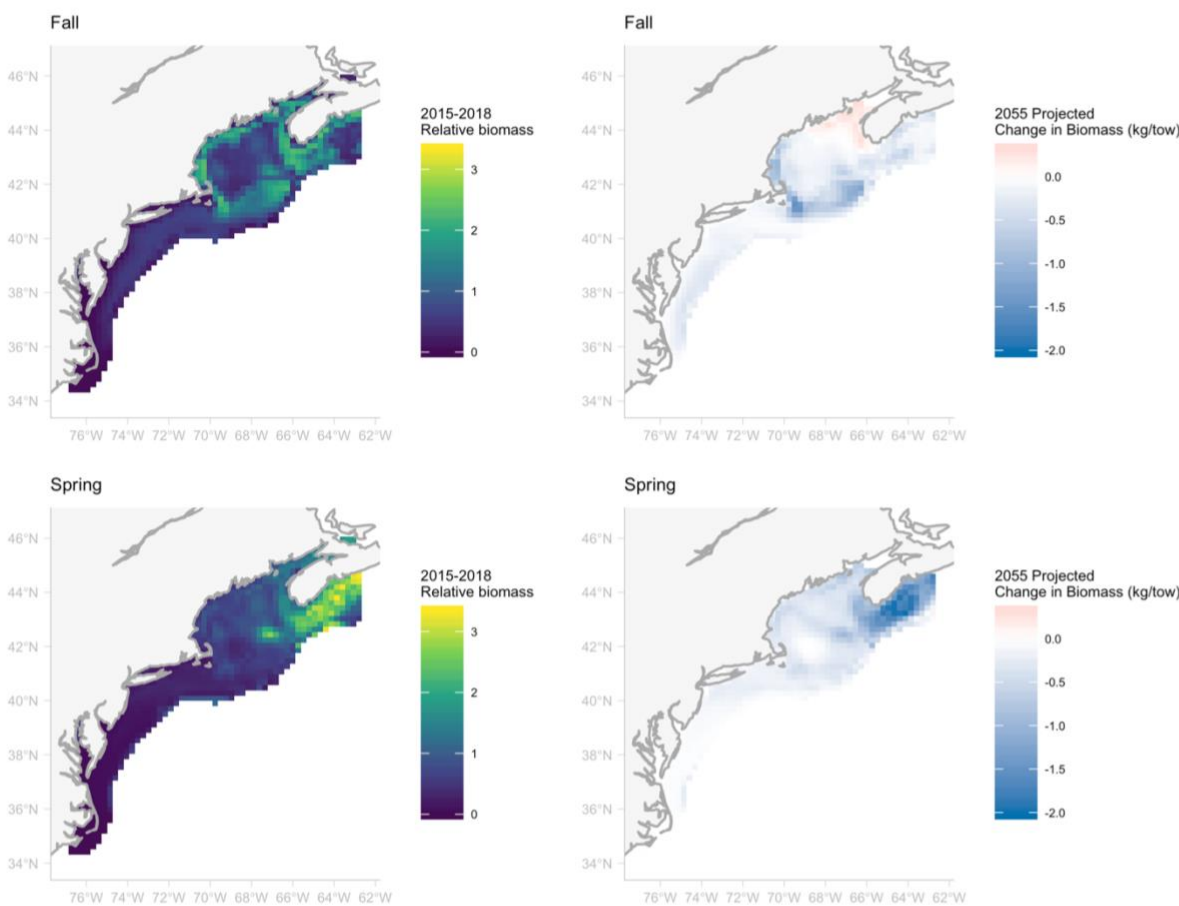

Figure 4. Average baseline predicted (2013-2018) and projected change (2055-baseline) in American lobster distribution and relative biomass given mean climate model ensemble RCP8.5 future temperatures.

Conclusions

In areas such as the southern Bay of Fundy and Nova Scotia, marine fisheries contribute substantially to the social, cultural, and economic fiber of many coastal communities. Understanding how the availability of species that support marine fisheries in this region may change in the future is foundational for understanding climate-related risks and vulnerabilities facing fishing communities, as well as for identifying potential new opportunities that may enable fishermen, fishing businesses, and coastal communities to successfully adapt.

We used species distribution models to project how the location and relative abundance of marine fish and invertebrate species may change by mid-century under a future climate scenario. On average, sea surface temperatures in the southern Bay of Fundy/Nova Scotia region are projected to be ~1.4°C higher in 2055 relative to a 2013-2018 baseline period. We incorporated this temperature increase into species distribution models, from which we gained insights into how the availability of different species may shift. These projections indicate future declines in many groundfish species, as well as in lobster, Northern shrimp, and Atlantic herring. However, as waters warm, projections also indicate that southern species may be able to move into the southern Bay of Fundy/Scotian Shelf region. Such species with projected increases include longfin squid, butterfish, summer flounder, black sea bass, and spot. These species may provide new opportunities for fisheries, but further investigation is needed to fully understand the coupled socio-ecological impacts of these distribution and abundance changes. While percentage increases in projected biomass are considerable for many of these species, the high percentages are driven by very low biomasses during the baseline period. It is unknown whether projected 2055 biomass levels would be adequate to support viable commercial harvest. Additional comparisons to existing fishing areas and input from Bay of Fundy fishermen will be needed to understand biomass thresholds at which catchability of the species would be sufficient for commercial targeting.

Finally, this initial effort is built on a fairly limited set of species observations that have been made in the Bay of Fundy/Scotian Shelf region by U.S. fishery surveys (e.g., NOAA NEFSC bottom trawl survey). We are near the final stages of developing a more sophisticated species distribution modeling framework that will be able to incorporate species observations from distinct surveys. This framework could be applied in the future to take in observations from both the NOAA NEFSC survey as well as from ongoing DFO surveys, an approach that would draw on a larger base of information and likely result in models with higher predictive performance.

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