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Shifts in Thermal Habitats in the Gulf of Maine under Climate Change: A Case Study on American Lobster

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May 15, 2017

A thesis submitted to the faculty of the Environmental Studies Program in partial fulfillment of the graduation requirements for the Degree of Bachelor of Arts with honors in Environmental Studies

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ABSTRACT

The rapid ocean warming observed in and predicted for the Gulf of Maine (GoM) raises uncertainties in the future distribution of American lobster (*Homarus americanus*). The location of lobsters is crucial to the long-term sustainability as well as management of Maine lobster fishery. This study provides a literature review of lobsters' thermal preferences in the summer lobstering season and analyzes high-resolution sea surface temperature data in Geographic Information System in order to predict the changes in thermal habitats in the GoM under different climate change scenarios. The results show a projected decrease in cooler thermal habitats (11-15 °C) and a projected increase in warmer thermal habitats (> 21 °C). Meanwhile, suitable thermal habitats (12-18 °C) for lobsters are estimated to grow in waters beyond the three-mile state water line under the high emissions scenario, presenting the possibility of offshore lobstering becoming a more lucrative option for lobstermen in Maine. The modeling of suitable habitats for lobsters made in this study will be more accurate if high-resolution bottom temperature data were used.

ACKNOWLEDGEMENTS

I would first like to sincerely thank my faculty advisor Loren McClenachan, Elizabeth and Lee Ainslie Assistant Professor of Environmental Studies, for her inspiring advices and patient guidance throughout the entire course of the project. I would also like to thank Philip Nyhus, Associate Professor of Environmental Studies, and Bruce Maxwell, Professor of Computer Science, for being my readers and providing valuable feedbacks.

I have received invaluable assistance from Randall Downer, Scientific Computing Administrator at Colby, who spent a fair amount of time helping me to compile the FVCOM ocean model. I would also like to thank Manny Gimond, GIS & Quantitative Analysis Specialist at Colby, for answering my questions regarding data collection and processing.

Finally, I would like to extend my appreciation to Jianhua Qi, Research Associate Professor at University of Massachusetts – Dartmouth, who kindly provided help with compiling the FVCOM ocean model and accessing existing FVCOM data.

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INTRODUCTION

Among the various biological impacts of climate change, potential changes in marine biodiversity and fisheries availability worldwide is an important yet complex topic that scientific studies recently start to focus on (Wernberg et al. 2011, Cheung et al. 2013). The Gulf of Maine (GoM) will be one of the hotspots for such ecological changes; it has witnessed warming at a rate faster than 99% of the areas in the world in the past decade (Pershing et al. 2015). Research also suggests a potential for 3 to 4 ºC warming in the Northwest Atlantic Shelf overall, if the amount of CO_2 in the atmosphere doubled (Saba et al. 2016).

The increasing ocean temperature is predicted to trigger distribution shifts in marine species (Cheung et al. 2009, Pinsky et al. 2012). Historically, shifts in the distributions of species have been one of the most immediate responses to temperature changes (Scavia et al. 2002, Parmesan and Yohe 2003). Recent studies have observed an on-going poleward shift of marine species around the globe due to climate change (Perry et al. 2005, Nye et al. 2009, Sorte et al. 2010). In addition to latitudinal shifts, depth-related changes in species distribution have also been predicted (Pinsky et al. 2013).

When it comes to potential distribution shifts of species living in the GoM, American lobster attracts a lot of attention, since it is arguably the most commercially important species in the area. The lobster fishery contributes substantially to Maine's coastal economy, constituting 80% of the value of Maine fisheries (Steneck et al. 2011). With landings at record high levels, the state of Maine produces more than half of the annual lobster landings in the U.S. (Fogarty et al. 2007, Berger 2014). The lobster fishery also contributes to the state's tourist economy, as summer tourists in coastal towns are drawn in part by the freshly caught lobsters served in restaurants (Berger 2014). However, this high reliance on lobster presents a risk. The relatively low catch diversity makes Maine coastal towns vulnerable to future change (Steneck et al. 2011, Colburn et al. 2016).

Therefore, this thesis aims to quantitatively model the potential changes in thermal habitats in the GoM under different climate change scenarios and analyze the corresponding impacts on the amount of habitats suitable for American lobster in the area.

Effects of Warm Water Temperature on Lobsters

The primary effect of warming water on American lobster (*Homarus americanus*) is with respect to distribution (Crossin et al. 1998). The geographic range of American lobster spans the continental shelf of the Northwest Atlantic from Newfoundland, Canada to offshore North Carolina, USA (Lawton and Lavalli 1995). However, lobster is sparsely distributed in areas south to New Jersey, with less than 0.1% of the U.S. landings coming from this area (Thunberg 2007). Within the core range (southern New England to the Bay of Fundy), the summer maximum surface temperature ranges from 12 ºC to mid-20's ºC (Fogarty et al. 2007). However, frequent warm conditions (> 20 ºC) have led to hypoxia in the southern range of the species, reducing the available nearshore habitats. Therefore, the current commercial lobster fishery ranges from mostly shallow nearshore waters in Maine to mostly deep offshore waters in southern New England (Berger 2014). Maine lobstermen commonly fish in the relatively warm 0-30 m area, where there is an abundance of legal-sized lobsters (Cooper et al. 1975).

Past observations indicate a strong likelihood of lobsters in Maine moving northward as ocean temperature in the Northwest Atlantic continues to rise. A previously observed northward shift occurred during a warming period between 1940 and 1955; in 1955, mean annual surface temperatures in Maine peaked 1.5 to 3.5 ºC above previous averages, with record landings reported in the northern range of the species (Dow 1969). This was followed by a southward shift of lobster abundance during the cooling period between 1956 and 1967 (Dow 1969). The recent increase of lobster landings in the GoM since the early 2000s also corresponds with a mean annual ocean temperature around 10 ºC, which is cooler compared to the rest of New England; the warmer ocean temperature in areas near the southern boundary (Long Island and northern New Jersey) restrict the lobsters there in cooler and deeper offshore waters (Fogarty et al. 2007).

This shift in distribution may be driven by lobsters' temperature threshold, which has been identified as between 18 and 20 °C. Experiments have revealed that adult lobsters tend to avoid water warmer than 20 °C, which is attributed to the fact that higher temperatures can increase the lobsters' respiration rates and weaken their immune systems, together showing as stress responses (Powers et al. 2004, Dove et al. 2005). The Atlantic States Marine Fisheries Commission (ASMFC) and lobstermen in southern New England have also attributed the decrease in inshore lobster recruitment in their region to the fact that ocean temperature consistently exceeds 20 °C in the summer (State of Connecticut 2009, ASMFC 2015).

Below this thermal threshold, there is a wide range of temperature that are suitable for lobsters to live in. Laboratory experiments demonstrated that adult lobsters acclimated to a summer ambient temperature in the GoM tend to stay in water between 13 °C and 19 °C (Crossin et al. 1998). This range is similar to the most suitable thermal range of 11.1 to 19.2 °C established based on trawl survey data (Tanaka and Chen 2015). Meanwhile, Steneck et al. (2013) proposed a slightly narrower temperature range from 12 to 18 °C as preferred thermal conditions for the GoM lobsters based on diver observations of postlarval swimming behavior. Environments warmer or cooler than this preferred range were associated with the lowest catch per unit effort (CPUE) in Great Bay Estuary, New Hampshire (Jury and Waston 2013).

Moreover, the optimal temperatures have been determined to be approximately 16 °C for both summer-acclimated adult lobsters and growing, postlarval lobsters (Crossin 1998, Annis 2005). Jury and Waston (2013) found that lobsters preferred 15.7 ± 0.4 °C in warmer months of a year. However, the optimal thermal condition for male and female adult lobsters appears to be slightly different. Males tend to select warmer environments than females do and were therefore more often captured in waters warmer than 16 °C (Jury and Waston 2013). The model of current distribution of lobsters in the GoM also shows significantly more males than females in warm nearshore waters (Chang et al. 2010).

Depending on the regional ocean temperature, adult lobsters are able to find thermally suitable habitats at different depths, ranging from the intertidal zone to offshore waters up to 700 m deep (Lawton and Lavalli 1995). From late spring to mid-fall, lobsters stay near shore and move within in the depth range of 0-30 m (Ennis 1984). In the summer, they mostly stay in shallow waters above the thermocline, which is at the depth of 5-10 m in the GoM (Ennis 1984, Waterman 2013). Water temperature drops drastically from 15 °C to below 10 °C within the thermocline and gradually decreases to 5 °C at depth (Maine Mathematics and Science Alliance 2011).

While changes in temperature are likely to affect the distribution of adult lobsters, ocean warming may exert positive effects on the reproduction and growth of lobsters in the GoM, including a prolonged growing season, faster growth, an earlier hatching season, and a smaller size at sexual maturity (Fogarty et al. 2007). For example, a moderate increase (a degree or two) in sea temperature in the GoM is predicted to provide more suitable settlement grounds for lobsters (Annis et al. 2013). Since the minimum temperature threshold for postlarval lobsters is 12 °C, if the eastern GoM began to experience bottom areas warmer than 12 °C during the summer, postlarval lobsters would be able to settle in this area that is previously too cold for them (Annis 2005, Fogarty et al. 2007). These newly available settlements on the eastern coast may be able to compensate the loss of hospitable grounds in the western GoM.

Changes in ocean temperature also affect the seasonal migration of American lobster. In the GoM, adult lobsters commonly move inshore in the spring and remain there over the summer, moving back to offshore waters in the late fall as nearshore waters become cooler and more turbulent (Cooper and Uzmann 1971, Chen et al. 2006a). Temperature-induced impacts on this migration pattern include earlier inshore migration in the spring and temporary movement into deeper waters during mid- to late summer when nearshore water temperature exceeds 20 ºC (Fogarty et al. 2007, Mills et al. 2013).

Predator abundance and diseases are also predicted to change under warming water scenarios (Wahle et al. 2009, Wahle et al. 2013). The decline in predator abundance, especially Atlantic cod (*Gadus morhua*), is considered a major contributing factor to the nearly tripled lobster landings in the U.S. northeast during the past 20 years (Berger 2014). Therefore, as the ranges of various fish species are predicted to shift north in the following decades, lobster populations may face increased predation from new species, such as black sea bass (*Centropristis striata*) and summer flounder (*Paralichthys dentatus*) (Shackell et al. 2014, Bell et al. 2015). An association also exists between warm ocean environment and the prevalence of Epizootic Shell Disease, which can significantly increase lobster mortality (Shields and Sainte-Marie 2013). Glenn and Pugh (2006) found a correlation between shell disease incidence in Buzzards Bay and a series of warmer than average water temperatures from 1999 to 2003, while much fewer cases of shell disease were observed in areas with cooler water temperature such as the GoM and the Outer Cape Cod during the same time period.

Implications for Lobster Fishery

The movements of lobsters in response to ocean temperature change can largely affect where commercial lobster fishery will be located in the future. Among the suite of potential temperature-driven shifts in the location of lobster stocks mentioned above, changes would be especially prominent in thermally heterogeneous areas such as estuaries and coastal habitats (Jury and Waston 2013). However, the tendency of Maine lobsters moving from inshore state water into deeper and cooler federal water has not been given as much attention as other possible shifts. The potential of such an offshore shift raises great uncertainties in the access and permitting of the fishery. Offshore landings historically only constituted a small percentage of total lobster landings in Maine but have recently started to see an increase, such as from 10% in 2008 to 24% in 2011 in lobster management zone D (Waterman 2012).

Offshore lobstering is becoming an increasingly lucrative choice, yet it requires a larger investment, especially in larger boats and fuel for long trips (Waterman 2012). Whether a lobsterman can travel long-distance to fish offshore on a day is also largely dependent on the weather condition. Additionally, fishermen need to obtain a federal permit in order to fish beyond the three-mile state water line, which only 20% of the Maine lobstermen possess right now (Schreiber 2016). Both the amount of federal permit holders in Maine and lobster landings from areas beyond the three-mile line have been increasing in the past few years (Waterman 2012). Finally, the increased density of offshore fishing boats could lead to more territorial disputes that cause loss of traps, as observed by Maine lobstermen (Waterman 2012). Therefore, an offshore shift of lobster population could challenge Maine lobstermen’s established fishing pattern and the state’s management scheme.

Meanwhile, changes in lobster seasonal migration patterns can exert both positive and negative impacts on the lobster fishery. For example, during the 2012 abrupt warming, lobsters moved inshore early and brought earlier and larger catches to Maine lobstermen, but the unexpected high landings exceeded the processing capacity and market demand for lobsters, resulting in an unexpected collapse in lobster prices (Mills et al. 2013). Similarly, although the more frequent inshore and offshore movement would not affect the total abundance of lobsters in a fishing zone, fishermen may find much fewer lobsters within the three-mile state water line, if coastal summer water temperature increases above 20 ºC more often in the future.

Results and Methods from Previous Studies

Past research has predicted a potential poleward shift of lobster habitats. Frumhoff et al. (2007) analyzed the possible impacts of different warming scenarios on American lobster. The researchers calculated an average of three global climate models to produce estimates for increases in bottom water temperature among different areas of lobster fishery in the 2080s compared to historical levels (1970-2000). For both western and eastern GoM, average bottom temperature is projected to increase by 1.1 to 1.7 °C in the low emission scenario and 2.2 °C in the high emission scenario (Frumhoff et al. 2007). Factoring these estimates into the current water temperature in the GoM and the thermal threshold of 20°C for lobsters, the range of suitable habitats for lobsters are projected to further decline in southern New England and expand into cold northern water, especially the eastern GoM and the Canadian coast. On a broader scale, Shackell et al. (2014) utilized bottom trawl survey data to build a species distribution model for 46 common species in the Northwest Atlantic, which generates a thermal habitat index for each species. Based on predicted bottom temperatures derived from projected sea surface temperatures for the year of 2060, their results show that lobsters will gain about 100% more of its current thermal habitat in Canada and about 25% more in the U.S. (Shackell et al. 2014).

While the two predictive studies mentioned above addressed latitudinal shifts, they did not specifically address the potential offshore shift of American lobster in the GoM. Therefore, a remaining question is the degree to which lobster range will shift from inshore state waters (0 – 3 miles nautical miles from shore) into offshore federal water (3 – 200 nautical miles from shore). In order to answer this question, one can build mathematical models based on trawl survey data in order to calculate either a habitat suitability index or an estimated density of lobsters (Chang et al. 2010, Tanaka and Chen 2016). These mathematical models include environmental factors such as bottom temperature, bottom salinity, depth, and bottom substrate. While these models were intended for the current distribution of lobster stocks, substituting projected bottom temperature for the current ocean temperature data in these models can help make reasonable predictions for lobster distribution in the future. Such method has already been used to predict the future distribution of squid in the Pacific (Alabia et al. 2015).

METHODS

I used Geographic Information System (GIS) to compare the projected ocean temperature for the GoM under high- and low- emission scenarios with the lobsters' thermal preferences during the inshore lobstering season (April to October). There are two common sources of ocean temperature data - surface temperature and bottom temperature. Surface sea temperature refers to the condition of the upper ocean (~10m) (Sprintall and Cronin 2001, Minnett and Kaiser-Weiss 2012). Since adult lobsters spend most of their time on the bottom of the ocean, which is usually deeper than 10 m, bottom temperature is preferred for describing lobsters' thermal habitats (Cooper et al. 1975, Lawton and Lavalli 1995). However, high-resolution sea bottom temperature is not currently available unless generated by ocean models. Meanwhile, high-resolution sea surface temperature data have been gathered through weather satellites. I explored the possibility of using both data sources in this study.

Bottom Temperature

I attempted to simulate high-resolution sea bottom temperature using the Finite-Volume Community Ocean Model (FVCOM) (Tanaka and Chen 2016). The horizontal resolution of this model varies with bathymetry, from 0.04 km in tidal creeks to 10 km near the shelf break (Chen et al. 2006b). Therefore, the modeling results at 0 – 30 m depth would be suitable for this study. I downloaded the source code for FVCOM 4.0 from the product's website (MEDML 2017). However, we ran into a series of problems during the compilation process. For example, in order to run the Fortran 90 codes with the Fortran compiler that Colby computers have, these codes need to be manually converted from .f90 extension to .F90 extension. After fixing all the extensions, we encountered namespace conflicts between the C codes of the NetCDF library and the Fortran codes of FVCOM object files. Due to the time constraint, we switched to use surface temperature data instead of modeling the bottom temperature.

Sea Surface Temperature

Because of these issues with the bottom temperature data, I instead used sea surface temperature data. I extracted the Sea Surface Temperature (SST) data for the GoM from the GHRSST GDS2 Level 2P Global Skin Sea Surface Temperature dataset (NOAA OSPO, 2015). These high-resolution SST data were collected by the Visible Infrared Imaging Radiometer Suite (VIIRS) on the Suomi NPP satellite. The spatial resolution is 0.75 km (along) x 0.75 km (across). The data were compiled every ten minutes, with an average temporal repeat of 12 hours.

I chose to use the SST data from one day in summer 2016 with the highest average daily temperature in Portland, ME (Weather Underground 2017). The area of GoM was covered by the satellite on that day partially at 17:00 and partially at 18:40. I extracted the longitude, latitude, and SST data in the nearshore area of the GoM from the two netcdf files in R (version 3.3.1) and loaded the data points into ArcGIS (version 10.3.1). All data are displayed in the WGS84 geographic coordinate system. Area is calculated after the data points are projected into the USA Contiguous Albers Equal Area Conic system. After converting the data points into a raster layer, I generated isotherms in 5 °C intervals starting at 11 °C within the study area for the current scenario and three different climate change scenarios - RCP4.5 (2050-2099), RCP8.5 (2006-2055), RCP8.5 (2050-2099). Under the RCP 4.5 high emissions scenario that assumes a radiative forcing of 4.5 W/m^2 in 2100, the SST in the GoM is projected to increase 2-2.5 °C by 2100 (NOAA, 2015). The RCP 8.5 high emissions scenario assumes a radiative forcing of 8.5 W/m^2 in 2100, in which case the SST in the GoM is projected to increase by 1.4-1.6 °C by 2055 and 3.2-3.6 °C by 2100 (NOAA, 2015). I omitted the RCP4.5 (2006-2055) scenario because its 1.2 °C is very close to the 1.4 °C increase in the RCP8.5 (2006-2055) scenario. I chose to generate the isotherms at 11 °C, 16°C, and 21 °C, because these isotherms represent the divisions between warmer surface thermal habitats (16-20 °C) and cooler surface thermal habitats (11-15 °C) based on a principal component analysis of thermal habitats in the northeast continental shelf presented in a previous study (Friedland et al. 2013). I also reclassified the raster layer based on these thermal groups in order to calculate the number of pixels in each group.

Because of lobsters' reliance on bottom habitat, I extrapolated bottom ocean temperature from the SST data. First, I divided the SST data into two parts - eastern GoM (well-mixed) and western GoM (with a thermocline) based on if the temperature in a pixel is less than 17 °C, because 17 °C isotherm line roughly corresponds to the east/west divide of the GoM shown in previous studies (Richaud et al. 2016). I uniformly subtracted 3 °C from the pixels in the eastern GoM. For the western GoM, I subtracted 1 °C at depth 0-10 m, 3 °C at depth 10-20 m, 4 °C at 20-40 m, and 6 °C for depth greater than 40 m. The relationship between temperature decrease and depth increase is based on existing vertical temperature profiles for the GoM (Maine Mathematics and Science Alliance 2011, Waterman 2013). I adjusted the specific values after comparing the generated bottom temperature, the lobsters' preferred thermal range, and the current lobster density maps produced in previous studies (Chang et al. 2010).

After extrapolating the bottom temperature from the SST, I added the predicted sea temperature increase onto the current bottom temperature. Under the RCP 8.5 high emissions scenario, the average bottom temperature in Northeast U.S. Continental Shelf system is expected to increase by at least 1 °C by 2050 and approximately 3 °C by 2100 (IPCC 2014, NOAA 2015). I reclassified the projected bottom temperature into different ranges of lobsters' thermal preference: (1) the thermal threshold of 20 °C, (2) the preferred range between 12 and 18 °C, and (3) the optimal condition of 16°C (a range between 15 and 17 °C was used).

Federal Permits

I geocoded the number of offshore lobstering permits associated with each principal port city based on a dataset of 2016 NEFMS federal permit records (GARFO 2016). I juxtaposed these data with the lobster management zones in Maine (Maine Coastal Atlas 2013).

RESULTS

Analyses have been done for both the entire study area (36,852 km^2), determined by the boundaries of the satellite data, and the Maine state water (7,315 km^2), bounded by three nautical miles from the shore.

Sea Surface Temperature

Under the RCP8.5 (2006-2055) scenario, changes in isotherms are moderate, with a slight shift to the east and a retreat from the inshore water on the southern tip (Figure 1b). Meanwhile, areas warmer than 21 °C are projected to expand in the western GoM, especially in the nearshore waters (Figure 1b). Under the RCP4.5 (2050-2099) scenario, the cooler thermal habitats (11-15 °C) decrease and shrink further to the east (Figure 1c). The warmer thermal habitats (16-20 °C) slightly decrease, while the area warmer than 21 °C increases significantly (Figure 1c).

On the other hand, the RCP8.5 (2050-2099) scenario is estimated to result in drastic changes in the location of isotherms. The warmer thermal habitats (16-20 °C) will completely shift to the eastern GoM, replacing the current cooler thermal habitats (11-15 °C) (Figure 1d). At the same time, the entire western GoM will become warmer than 21 °C (Figure 1d).

Overall, as the increase in temperature becomes greater, both the 11-15 °C group and the 16-20 °C group decrease while the area warmer than 21 °C increases (Table 1). Notably, under the RCP8.5 (2050-2099) scenario, the cooler thermal habitats (11-15 °C) will decrease to only 4.5% of the study area, whereas areas warmer than 21 °C will reach 56.4% of the study area (Table 1). When looking at changes in the size of these

Table 1. Percentage of pixels in each Sea Surface Temperature (SST) range in the entire study area under the current situation and three climate change scenarios.

SST (°C)	% of Pixels in Each Temperature Range			
	Current	RCP8.5 (2006-2055)	RCP4.5 (2050-2099)	RCP8.5 (2050-2099)
<5	5.14	4.52	4.27	3.74
5~10	3.21	2.81	2.76	2.63
11~15	**22.03**	**15.90**	**12.66**	**4.51**
16~20	50.48	45.73	42.74	32.78
>20	**19.14**	**31.04**	**37.57**	**56.35**
Total	100.00	100.00	100.00	100.00

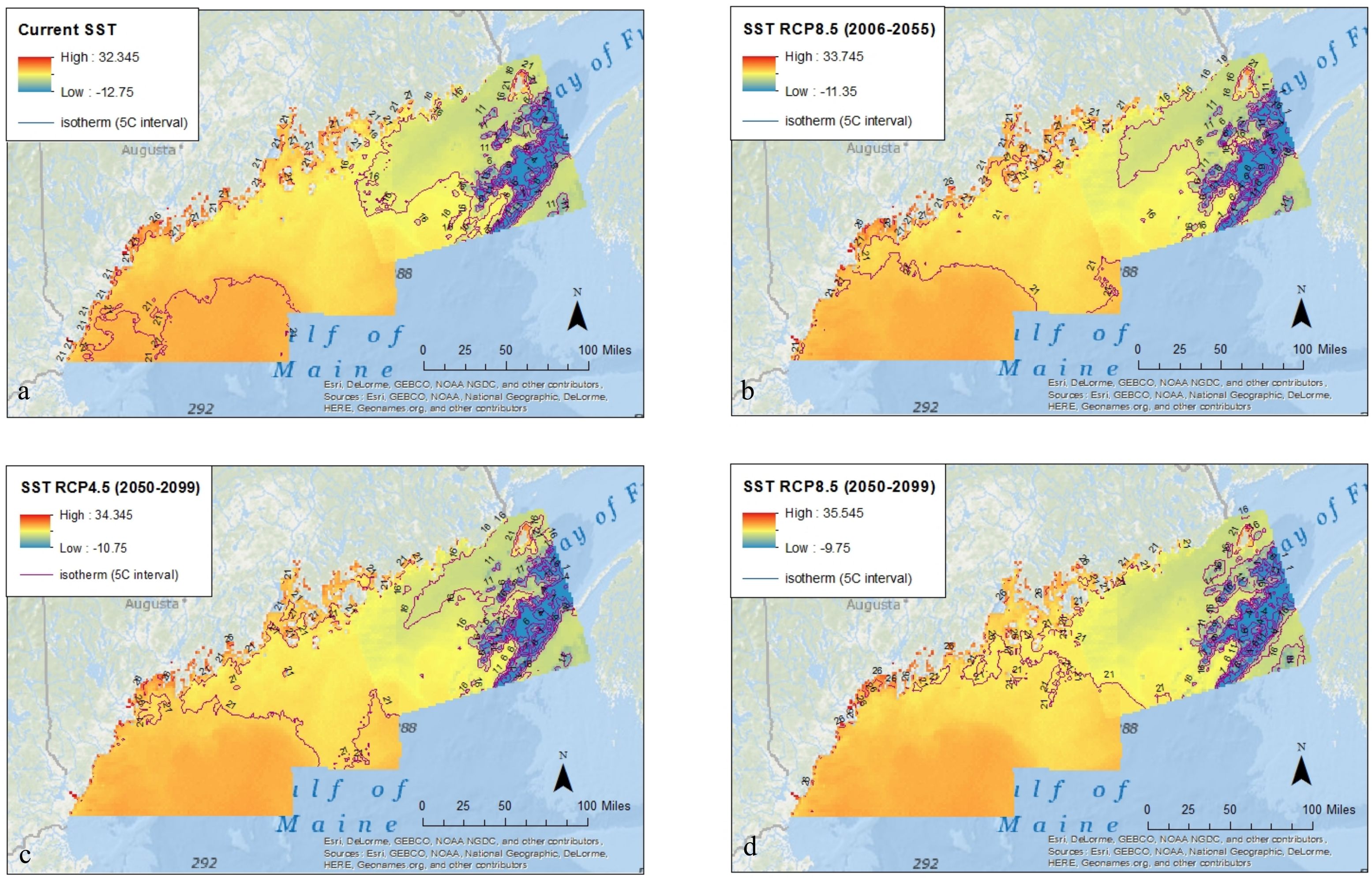

Figure 1. Sea Surface Temperature (SST) with isotherms at 11 °C, 16°C, and 21 °C in (a) the current scenario, (b) the RCP8.5 (2006-2055) scenario, (c) the RCP4.5 (2050-2099) scenario, and (d) the RCP8.5 (2050-2099) scenario.

thermal habitats, there will be a loss of 6,456 km^2 in 11-15 °C waters and an expansion of 13,712 km^2 in waters warmer than 21 °C.

In the RCP4.5 (2050-2099) scenario, 32.0% of the state water will experience a shift in the thermal habitats (i.e. moved from the 11-16 °C group to the 16-20 °C group). These projected changes fall into three clusters in the western, central, and eastern part of the gulf respectively. In contrast, the RCP8.5 (2050-2099) scenario will lead 64.8% of the state water into such a shift. Most state waters on the western and eastern tips will experience changes in thermal conditions (Figure 2).

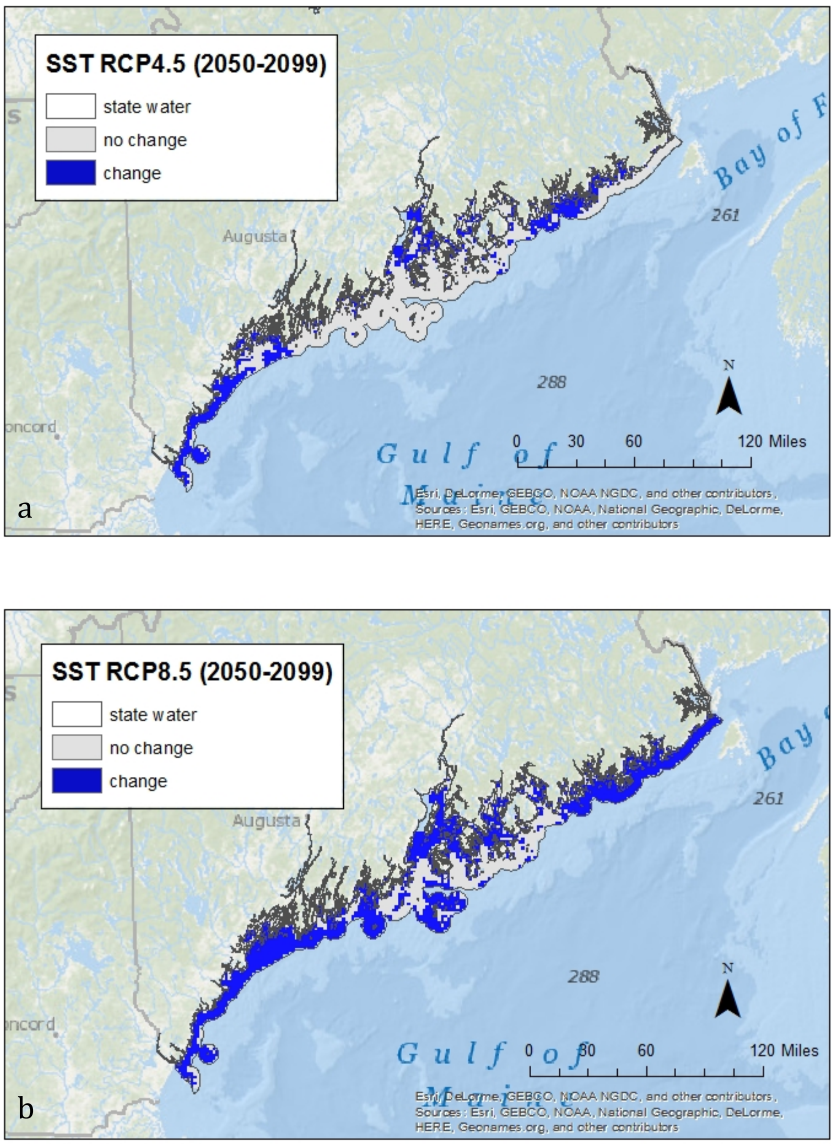

Figure 2. Changes in thermal habitats in Maine state water under (a) the RCP4.5 (2050-2099) scenario and (b) the RCP8.5 (2050-2099) scenario.

Bottom Temperature

The extrapolated bottom temperature in both RCP4.5 and RCP8.5 scenarios were compared with the current levels. Under the RCP4.5 scenario, the area cooler than 12 °C shrinks and offers room to more 12-18 °C area in the central and eastern part of the gulf (Figure 3a). The 12-18 °C area expands from 49.0% to 66.2% of the study area, which translates to an increase of 6,339 km^2 (Table 2). Meanwhile, there is a slight increase in areas warmer than 20 °C in the state water, from 10.0% to 13.8%. The 12-18 °C area within the state water remains approximately the same (Table 3).

Under the RCP8.5 scenario, even more of the offshore federal waters in the study area fall into the 12-18 °C group, leading to 80.6% of the study area covered by the 12-18 °C range (Table 2; Figure 3b). This change also means an increase of 11,645 km^2 in 12-18 °C waters. Meanwhile, areas warmer than 18 °C increase significantly in the state water, especially on the southern tip (Figure 3b). These warmer areas constitute 36.1% of the state water in this scenario, while they only make up 18.9% of the state water currently (Table 3).

Table 2. Percentage of pixels in each of the lobsters' thermal preference ranges in the entire study area under the current, low-emission, and high-emission scenarios.

Bottom	% of Pixels in Each Temperature Range		
Temperature (°C)	Current	Low Emission (1°C)	High Emission (3°C)
<12	46.04	27.38	9.43
12~18	**48.99**	**66.17**	**80.62**
18~20	2.14	2.67	3.50
>20	2.83	3.78	6.44
Total	100.00	100.00	100.00

Table 3. Percentage of pixels in each of the lobsters' thermal preference ranges in Maine state water under the current, low-emission, and high-emission scenarios.

Bottom	% of Pixels in Each Temperature Range		
Temperature (°C)	Current	Low Emission (1°C)	High Emission (3°C)
<12	28.44	17.11	0.00
12~18	52.64	57.25	63.85
18~20	8.90	11.83	10.51
>20	10.02	13.81	25.64
Total	100.00	100.00	100.00

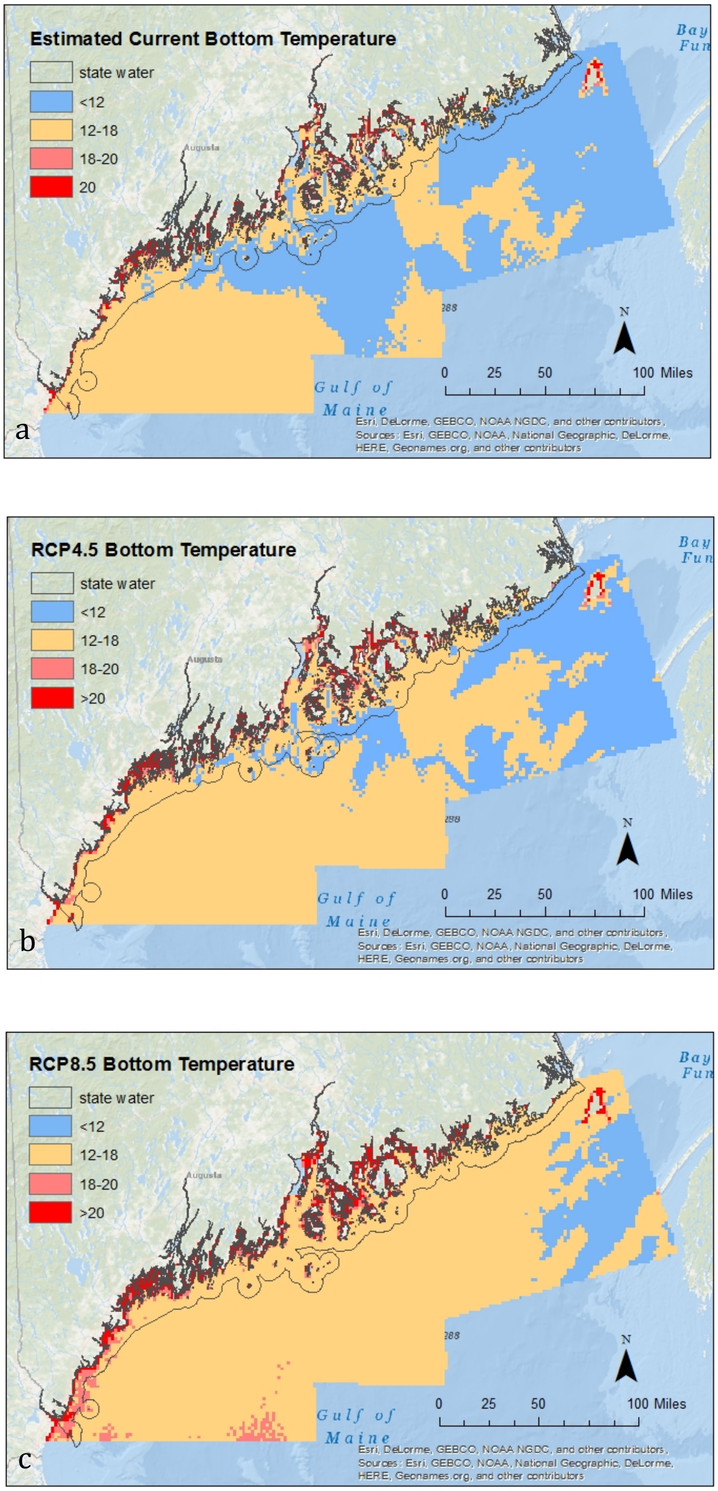

Figure 3. (a) Current (estimated) sea bottom temperature, (b) projected sea bottom temperature under the RCP4.5 (2050-2099) scenario, and (c) projected sea bottom temperature under the RCP8.5 (2050-2099) scenario reclassified into lobsters' thermal preference ranges (<12 °C, 12-18 °C, 18-20 °C, and >20 °C).

When classified based on the 15-17 °C thermal range under the RCP4.5 scenario, 73.5% of the study area is projected to be cooler than 15 °C (Table 4; Figure 4a). Only 14.4% of the state water and 18.8% of the entire study area fall into the optimal 15-17 °C range (Figure 4a). These areas with the optimal temperature range concentrate in the southern-most region of the gulf (Figure 4a).

Table 4. Percentage of pixels in each thermal range (<15 °C, 15-17 °C, >17 °C) in the entire study area for the low- and high-emission scenarios.

Bottom Temperature (°C)	% of Pixels in Each Temperature Range		
	Current	Low Emission (1°C)	High Emission (3°C)
<15	90.06	73.49	46.04
15~17	3.50	18.83	27.45
>17	**6.44**	**7.68**	**26.51**
Total	100.00	100.00	100.00

Under the RCP8.5 scenario, areas in state water that are warmer than 17 °C are projected to increase from the current 25.6% to 44.7% (Table 5). The southern-most portion of federal water will also be warmer than 17 °C, while the majority of the central and eastern gulf remains cooler than 15 °C (Table 5; Figure 4b). Specifically, areas warmer than 17 °C in the entire study area increases from 7.7% in the low-emission scenario to 26.5% in the high-emissions scenario (Figure 4). The 15-17 °C optimal zone will expand from 3.5% to 27.5% of the study area and undergo an eastward shift in this high-emission scenario (Figure 4b).

Table 5. Percentage of pixels in each thermal range (<15 °C, 15-17 °C, >17 °C) in Maine state water for the low- and high-emission scenarios.

Bottom Temperature (°C)	% of Pixels in Each Temperature Range		
	Current	Low Emission (1°C)	High Emission (3°C)
<15	63.85	55.32	28.44
15~17	10.51	14.39	26.88
>17	**25.64**	**30.30**	**44.68**
Total	100.00	100.00	100.00

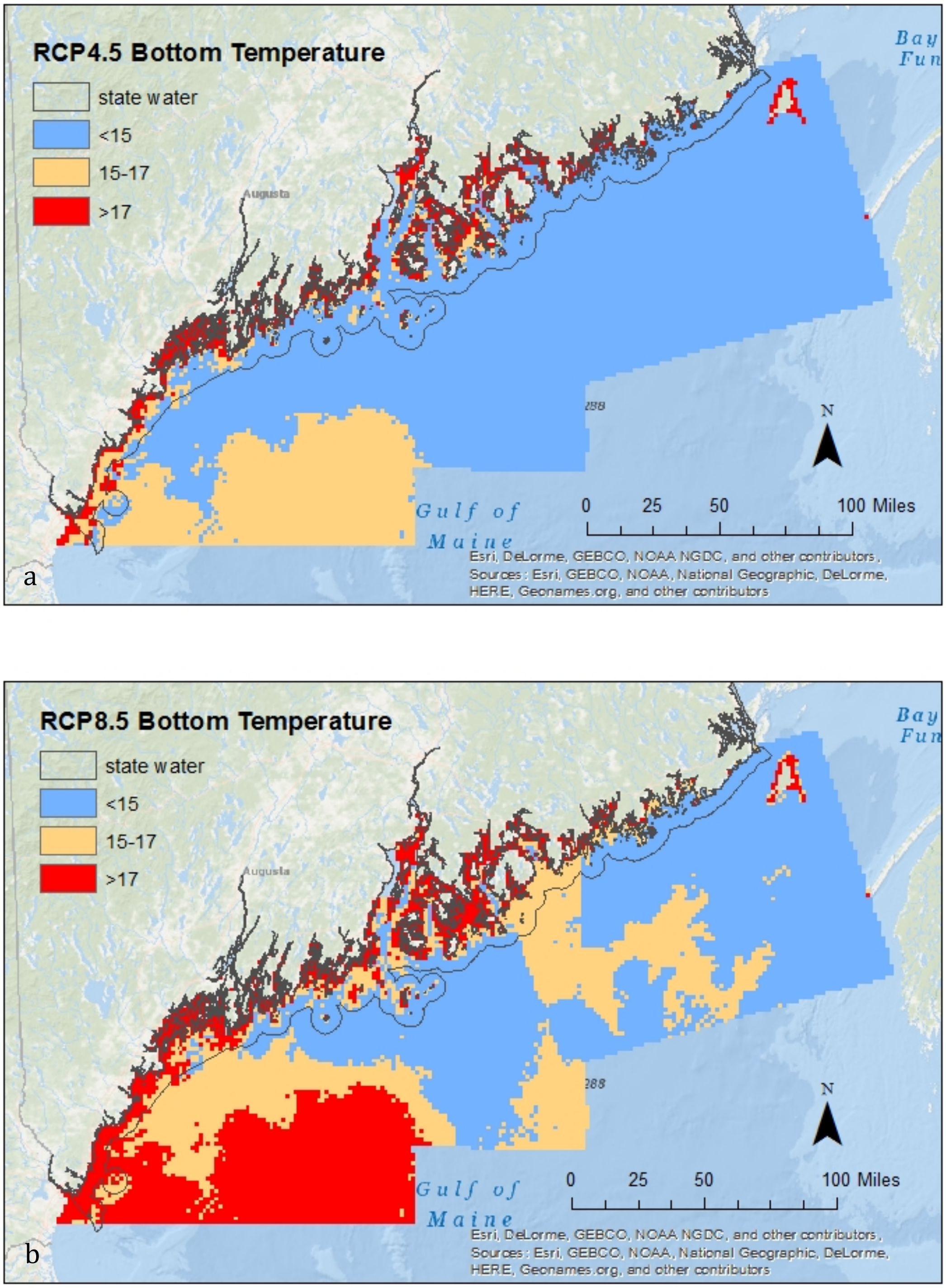

Figure 4. (a) Projected sea bottom temperature under the RCP4.5 (2050-2099) scenario and (b) projected sea bottom temperature under the RCP8.5 (2050-2099) scenario reclassified into lobsters' thermal preference ranges.

Federal Permits

In 2016, fishing vessels with federal lobstering permits are most concentrated in the ports of Portland, Stonington, Jonesport, Beals, Friendship, and Harpswell (n>40). These ports distribute evenly across the different lobster management zones.

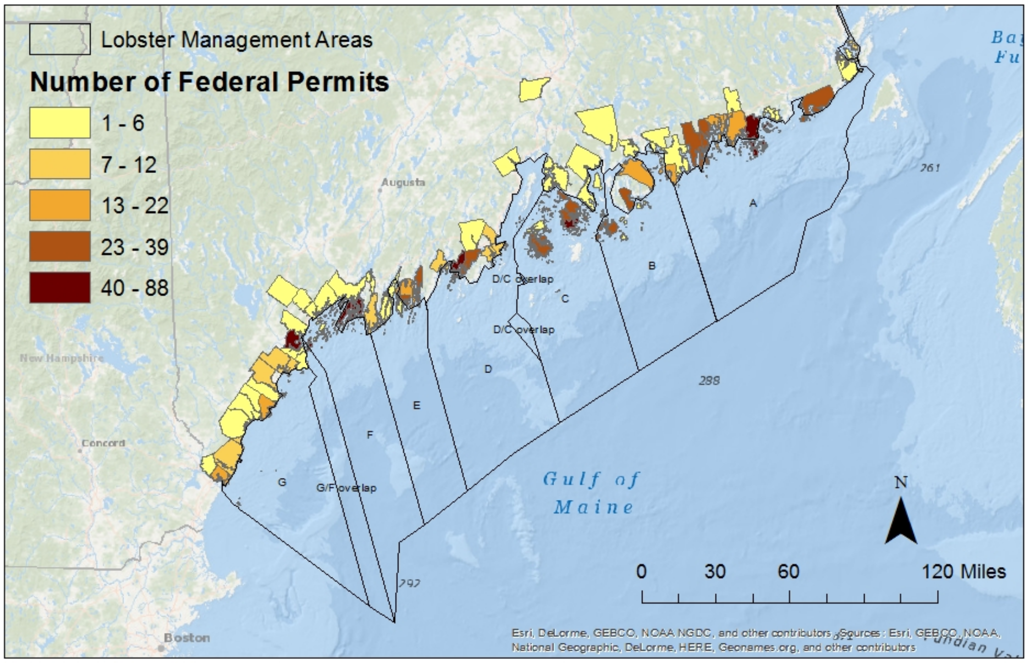

Figure 5. Number of federal lobstering permits associated with each principal port city and the border of Maine lobster management areas.

DISCUSSION

Key Findings and Limitations

My results demonstrate that surface thermal habitats in the GoM will shift eastward and result in a change in the availability of desirable thermal habitats for particular species in the area. One clear trend will be the loss of 6,456 km^2 in 11-15 °C cooler thermal habitats, which have been considered as the core habitats in the northeast continental shelf ecosystem (Friedland et al. 2013). I also found that the 16-20 °C warmer thermal habitats will contract, while areas warmer than 21 °C will increase substantially by 13,712 km^2. This pattern is consistent with the historical trend between 1985 and 2010 that Friedland et al. (2013) identified, where the 11-15 °C group decreases across time, and the 21-27 °C group significantly increases. Moreover, the thermal composition of GoM is predicted to gradually switch from 16-20 °C dominated to >21 °C dominated. In particular, under the RCP8.5 (2050-2099) scenario, 64.8% of Maine state water will witness a shift into a warmer thermal habitat at the same locality.

Meanwhile, based on the extrapolated bottom temperature, I found that the GoM will continue to provide suitable habitats (12-18 °C) for American lobster even after the 3 °C bottom temperature increase under the RCP8.5 (2050-2099) scenario. There will be an increase of areas warmer than 20 °C in Maine state water, from 10% to 25%, mostly in the coastal areas and estuaries. Nevertheless, areas between 12 and 18 °C are projected to increase substantially from 49% to 81% in the entire study area, which translates into 11,645 km^2 of additional suitable habitats for lobsters.

While many existing studies focus on temperature-driven distribution shifts of marine species on the global or regional level and identified meaningful patterns such as a poleward shift, this thesis takes a close look at a single species, American lobster, specifically in the nearshore area of the GoM. The small geographic scope makes high-resolution modeling and analyses possible, but this thesis also reveals many challenges associated with the use of such methodology. High-resolution bottom temperature data is the key for identifying suitable thermal habitats of marine species in the GoM, where most of the commercially important fish are bottom dwellers, such as American lobster and Atlantic cod (Richaud et al. 2016). However, such dataset is not currently available due to the high cost of data collection. Generating estimates for bottom temperature from ocean models such as FVCOM is a possible alternative option if one has sufficient time to set up the model or has access to machines that already have the software running. On the other hand, extracting SST for a small area from a global satellite dataset requires either machines with relatively high computation capacity or additional processing of the raw data through coding. This thesis presents a feasible procedure of the latter (Appendix).

The extrapolation from SST to bottom temperature in this study provides simplified and imprecise estimates for the bottom thermal conditions. With high-resolution current and projected bottom temperature data for the GoM, a similar geospatial analysis can yield more accurate predictions of the availability of suitable thermal habitats for lobsters or other species in the GoM, where rapid warming is occurring and fisheries are already witnessing range shifts (Cheung et al. 2009, Pinsky et al. 2012, Pershing et al. 2015). While the thermal condition on the ocean bottom is related to that on the surface, SST data is better suited for identifying broad-scale changes than predicting the movement of particular fish species. In addition, this study used temperature data from the warmest day of the year, which to a degree produces projections for the worst-case scenario. Fairer estimates for future thermal conditions in the GoM can be made through calculating the average SST over each season. Furthermore, while temperature is a major predictor of lobster distribution, other factors including the bottom substrate, water salinity, ocean currents, as well as ocean acidification affect lobsters' choice of habitats as well. In addition, the level of fishing efforts also affects the abundance of lobsters in a certain area, so cautions need to be taken when predicting lobster distribution solely based on ocean temperature.

Implications for Fisheries Management

The decrease in cooler thermal habitats (11-15 °C) can lead to biological consequences such as a decline in the abundance of certain zooplankton species that feed Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) larvae (Buckley and Durbin 2006, Friedland et al. 2013). Such a decline in zooplankton populations can therefore impose a negative impact on the productivity of species on the higher trophic level. Meanwhile, an increase of areas warmer than 16 °C can potentially offer desirable thermal habitats for species that do not typically live in the GoM, such as black sea bass (*Centropristis striata*) (Steneck et al. 2013). Although sea surface temperature is not directly associated with the habitat preferences of bottom-living fish species, changes in SST may perpetuate through the food chain and still affect the behaviors of a fish species. This complex relationship between ocean temperature and distribution of marine species reveals the importance of adopting an ecosystem approach when investigating the impacts of ocean warming on a particular species, as the distribution and abundance of its prey and predators will experience changes at the same time.

Under the current warming trends in the GoM, lobstermen might opt to pursue offshore fishing as the number of lobsters remaining in cool, deep water beyond the state water line in the summer increases. Since thermal conditions in the federal water will remain suitable until 2100, switching to offshore lobstering might be cost-effective for Maine lobstermen. A bigger vessel will be an essential investment for many inshore lobstermen, because their current fleets are commonly small and only make day trips (Schreiber 2016). In 2016, the average fleet length associated with the 1230 federal permits for lobstering in Maine is 38 feet, a size at which multi-day operations in offshore water will be feasible (GARFO 2016). Moreover, 85% of the federal permit holders only use their permit for lobstering (GARFO 2016). If the warming trend in the GoM persists in the late 21st century, Maine lobstermen would need to think twice before devoting huge investments into offshore lobstering, as suitable habitats for lobsters may eventually start to decrease and the choices to diversify their fishing efforts with these larger vessels are relatively limited. Moreover, obtaining a new federal permit can be difficult as well. There is currently a long waiting list for attaining federal lobstering permits in Maine since the limited entry system was put in place in all zones except zone C in or after 2009 (DMR 2016). New entrants are only granted a license when the zone-specific exit ratio is met (DMR 2012). The turnover rate is therefore low. Fishermen who applied between 2005 and 2009 still remain on the waiting list in 2016 (DMR 2016).

The tendency of lobster fishery moving offshore can help relieve the inshore congestion that lobstermen currently face but add more pressure to the territory competition in federal waters. For example, as the western GoM gets warmer, offshore lobstering can become more lucrative in the central and eastern part of the gulf. However, it will not be easy for lobstermen to follow the movement of lobsters, as their license is confined to one of the A - G management zones, which are perpendicular to the coast. Currently, ports with a large amount of offshore losbtering vessels distribute evenly along the coast, suggesting a balance in lobstering efforts in federal water across different management zones. If a lobsterman were to switch zones, however, he/she will have to join the same waiting list for each zone as mentioned above (DMR 2012). Changes in relative abundance of lobsters in neighboring zones can trigger a larger demand of zone switches, which can lead to a even longer waiting time than there currently is.

In conclusion, predicting changes in species distribution in response to climate change can provide valuable insights into the long-term lobster fishery management in Maine, as both lobstermen and policymakers need to adjust their practices based on the poleward and offshore shift in lobsters' distribution. Periodical evaluations of the availability of lobsters in the GoM, especially in the state water and in the western part of the gulf, will be crucial. Such assessments help to determine the major goal of lobster management, as in whether it shall focus on enabling easier transitions and equitable access to offshore, eastward-moving fishing efforts or on the preparatory diversification of commercial fishery in the case of intensified warming.

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APPENDIX

Sample R Code:

```
library(ncdf4)
library(reshape2)

# open a netCDF file
ncname <- "20160722184000"
ncfname <- paste(ncname,".nc", sep="")
dname <- "tmp"  # note: tmp means temperature (not temporary)
ncin <- nc_open(ncfname)

# store the desired indices in two variables
niStartIdx <- which( ncin$dim$ni$vals == 1)
njStartIdx <- which( ncin$dim$nj$vals == 550)

# extract and write out the SST data
sst <- ncvar_get( ncin, ncin$var$sea_surface_temperature, start= c(niStartIdx, njStartIdx,
1), count= c(50,50,1))
meltedSST <- melt(sst)
write.csv(meltedSST, file = "sst07221840_ni1nj550_count50.csv")

# extract and write out the latitude data
lat <- ncvar_get( ncin, ncin$var$lat, start= c(niStartIdx, njStartIdx), count= c(50,50))
meltedLat <- melt(lat)
write.csv(meltedLat, file = "Lat07221840_ni1nj550_count50.csv")

# extract and write out the longitude data
lon <- ncvar_get( ncin, ncin$var$lon, start= c(niStartIdx, njStartIdx), count= c(50,50))
meltedLon <- melt(lon)
write.csv(meltedLon, file = "Lon07221840_ni1nj550_count50.csv")

nc_close(ncin)
```