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Northern Shrimp in the Gulf of Maine and the Impacts of Climate Change

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ABSTRACT

Northern Shrimp (*Pandalus borealis*) populations within the Gulf of Maine collapsed in 2011 following the first year that sea surface temperature surpassed 10ºC. The population collapse resulting in a moratorium in 2014. The waters of the Gulf of Maine have been rising at a rate of 0.045ºC per year, changing predator distribution, prey distribution, as well as Northern Shrimp biological variables. There has been very little recovery to the Northern Shrimp stock despite the fishing moratorium and the answers behind the collapse and lack of recovery remains enigmatic. Therefore, this two-chapter study includes a literature review and a research paper trying to determine the factors and mechanisms behind the Northern Shrimp population crash. The first chapter is a literature review investigating the direct and indirect impacts of increasing water temperatures on the Northern Shrimp stocks in the Gulf of Maine and Eastern Canada. The second chapter is a research paper addressing the question: Are there any patterns between SST and Northern Shrimp biological variables in either the GOM or the Scotian Shelf? The results demonstrate a possible temperature threshold of 10.1ºC for sea surface temperature and 8.1ºC for bottom temperature that above results in both biomass and spawning stock biomass collapse. Temperatures above these thresholds demonstrate high mortality rates in Northern Shrimp larvae and adults. The implications of these findings include Northern Shrimp fishery never returning to the Gulf of Maine and the Scotian Shelf in Eastern Canada possibly being the next location to experience the population collapse.

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Finally, I would like to acknowledge and communicate my respect to the indigenous communities that have lived on these ancestral lands and will in the future. Colby College and the land around the Gulf of Maine where I studied are the ancestral and unceded land of the Wabanaki Peoples.

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CHAPTER ONE:

A Literature Review: Shrimp Population Response to the Direct and Indirect Effects of Warming Ocean Waters in the Gulf of Maine and Eastern Canada

Introduction

Shrimp populations are present in oceans all over the world, and act as an important part of the ecosystem; occupying the lower trophic levels and acting as both predators and prey in the ocean (Krumsick & Fisher, 2022). Over 2000 different species of shrimp exist ranging in size, morphology, and habitat type. Some of the more well-known species include the Giant Tiger shrimp, Pink shrimp, Brown shrimp, and even Northern shrimp. Northern shrimp (*Pandalus borealis)* are located in the Northern Hemisphere of Earth in the cold waters of the North Pacific, North Atlantic, and Arctic Oceans (NOAA, 2024). In the US, Northern shrimp are found off the coast of Washington and Maine. In Maine, Northern shrimp had been a large part of the fishing industry. The fishery began in the coastal waters in the late 1930s and the fishery thrived, moving into offshore year-round fishing in the late 1960s (Clark et al., 2000). But when recruitment (new individuals are added to a population through birth, immigration, or maturation) began to fail, the fishery collapsed leading to a moratorium being put into place in 2014 (Hunter et al., 2021). The Northern shrimp population collapse is now thought to be due to climate change which caused the waters to warm and disrupted northern shrimp interactions such as trophic levels, diseases, predators, and more (Hunter et al., 2021). The Gulf of Maine (GOM here forward) has experienced the impacts of climate change on its waters at a faster rate than any other oceanic body of water (Pershing et al., 2021). Therefore, the GOM could be a predictor of what could happen to Northern Shrimp populations in other locations if climate change continues at its current rate of warming. Eastern Canada still has a Northern Shrimp population as well as an active fishery, but that might change as the waters become warmer. The total biomass estimate for Northern shrimp in Eastern Canada decreased by 29% in only one year from 2020 to 2021 (DFO, 2022). Understanding Northern Shrimp populations requires understanding their unique biology and ecology as well as the history of shrimp fishing to be able to determine the best methodologies for population preservation.

Northern shrimp (*Pandalus Borealis)* is a species of Caridean shrimp located in the colder waters of the Northern Hemisphere. They typically live in muddy high-organic-content soft bottom areas of the ocean in depths ranging from ~30 to ~1000 feet deep with a water temperature from 2 - 6 ºC (NOAA, 2024). Northern shrimp are protandrous hermaphrodites which means that they hatch as males and then transform into females. The males reach sexual maturity at around 2.5 years and then they transform into females at around 3.5 years and live the rest of their life out as females (NOAA, 2024). The mature females mate in the late summer or early fall before moving to shallower waters during the winter. The females carry the fertilized eggs for about 8 months before they are released (NOAA, 2024). The Northern Shrimp hatch and feed near the surface for 2 to 3 months before settling at the bottom as post-larvae (Ouellet & Allard, 2006). They then move into a juvenile stage until they reach sexual maturity and become an adult. Throughout each life stage, they shed their exoskeleton to be able to grow (DFO, 2022). Northern Shrimp mainly prey on detritus, small zooplankton, large zooplankton, and phytoplankton (DFO, 2022). They play an important role in the marine ecosystem as they are heavily preyed upon by Hake, Cod, Longfin Squid, and Redfish (DFO, 2022). They are also a very economically important species and fisheries were developed to be able to fish and then sell these shrimp (Clark et al., 2000).

Northern shrimp are typically caught in the winter due to the egg-bearing females being closer inshore due to the warmer waters for their eggs to be released (NOAA, 2024). The females move to the warmer waters so that there is a higher chance of survival for their eggs because they are more sensitive to temperature (NOAA, 2024). The females also move closer to shore to ensure the eggs don't fall off the continental shelf when they are released (NOAA, 2024). Otter trawls are typically used to harvest shrimp (NOAA, 2024). Otter trawls are bottom-fishing gear that have heavy plates or otter boards that weigh down either side of the trawl as floats and headropes keep the mouth of the trawl open. They are dragged forward and scrape the muddy, soft bottom floor to pick up any of the shrimp living down there (NOAA, 2024). There is minimal impact on the habitat due to the muddy seafloor not having much structure as well as the trawl creating more drag so the trawlers can't move very quickly over the habitat (NOAA, 2024). Some fishermen can also use traps to catch Northern Shrimp, however traps are less common than otter trawls. Bycatch is limited (~2%) as the fishermen target the specific habitat where shrimp will be and only target the seafloor (NOAA, 2024). There also is a minimum mesh size to prevent any male shrimp from getting caught (NOAA, 2024). This occurs because the larger mesh will allow the smaller, male shrimp to escape out of the holes in the mesh. They also use finfish excluders and size sorting devices to prevent the bycatch of groundfish as well (NOAA, 2024).

The Northern Shrimp fishery began in the Northeastern United States in the 1930s with very few landings before the fishery took off (Clark et al., 2000). Up until the late 1960s, the fishery mainly operated inshore but it expanded to offshore in the late 1960s, bringing the peak landings up to 12,800 tons (Clark et al., 2000). Inshore fishing is state waters that are 0-3 miles away from the coastline and offshore fishing and 3-200 miles away from the coastline (Clark et al., 2000). However, in the 1970s Northern shrimp recruitment plummeted, resulting in fishery landings dropping (see Figure 1.) (Clark et al., 2000). This decline in recruitment could be attributed to the collapse of the Silver Hake fishery which resulted in a lot of fishermen changing to the shrimp fishery (Charleson, 2020). The quantity of boats in the shrimp fishery rose from 102 in 1964 to over 300 in 1970 (Charleson, 2020). The fishery was temporarily shut down in 1978 due to the stock collapse (Clark et al., 2000). The fishery slowly began to recover and was reopened in 1979, reaching stability of around 3,000-4,000 tons per year in the early 1990s which was about 17% of the global harvest (Clark et al., 2000). In 1996 there was another peak in Northern shrimp landings before the population dropped (Clark et al., 2000). Again, the population slowly began recovering up until another population collapse in 2014 (Clark et al., 2000). In the four years leading up to the 2014 collapse, the fishery had to be shut down early due to commercial fishermen exceeding the catch limit (Clark et al., 2000). In both the 1970s and 2014 the shrimp population collapse could be attributed to overfishing or large influx in fishing resulting in overfishing. A moratorium was put into place which banned fishing and harvesting of Northern Shrimp (Clark et al., 2000). This was to allow for possible population growth and recovery in the population and recruitment but very little has been noted since the 2014 moratorium was put in place (Clark et al., 2000). Recruitment is dependent on spawning stock biomass and ocean temperatures and neither of those have improved since the collapse (Clark et al., 2000).

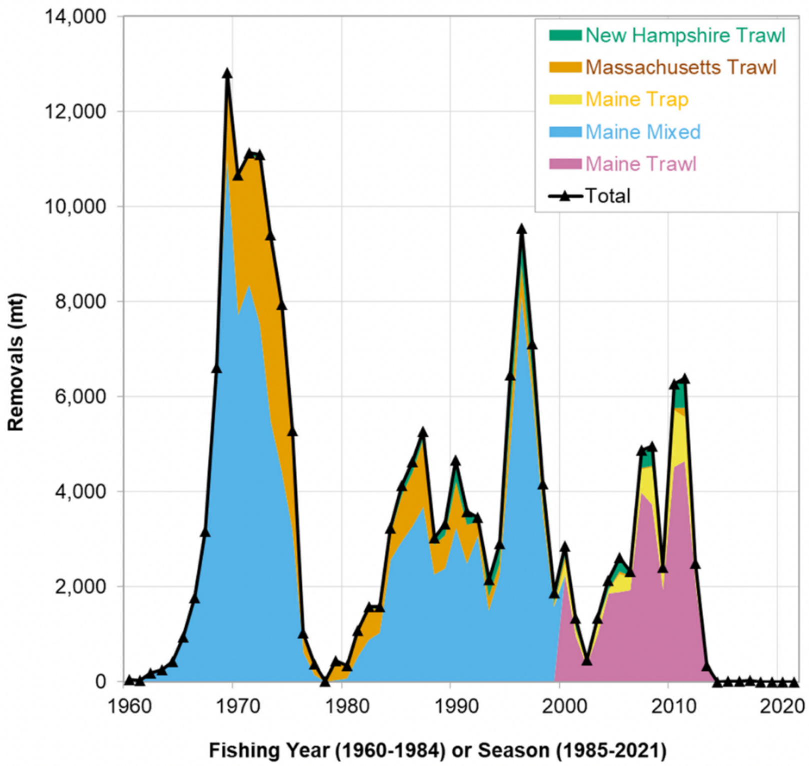

Figure 1. Northern Shrimp Landings Data from the GOM from 1960 to 2021 based on state and gear type (NOAA, 2021)

The nearby Northern Shrimp fishery in Eastern Canada can provide a useful comparison because it also has a Northern Shrimp population and fishery but its waters are cooler than that of the GOM. The main fisheries in Eastern Canada are off the coast of Nova Scotia, in the Gulf of St. Lawrence, in the Davis Strait, and off the coast of Labrador and northeastern Newfoundland (See Figure 2.) (DFO, 2022). These fisheries have continued to harvest Northern shrimp, but the landings continue to decline. The Eastern Canada fishery began in the 1970s with it being divided between inshore and offshore fishing (DFO, 2018). The Eastern Canada fishery is substantially larger than the GOM fishery as it is all along the coast of Eastern Canada. The GOM fishery only exists in the section of ocean from the outer point of Maine and Nova Scotia down to Cape Cod, Massachusetts. The GOM has warmer waters and less circulation than the coast of Eastern Canada. The population continued to increase until the mid-2000s when population size began to decline in several zones of the fishery (DFO, 2018). These declines were thought to be attributed to changing oceanic conditions and warming (DFO, 2018). In 2011, fishing was suspended in one section of the fishery (SFA 7) and then reopened a year later (DFO, 2018). However, in 2015, the SFA 7 section was suspended again and has been closed to directed fishing since (DFO, 2018). It was closed due to the declining biomass and concern for the sustainability of the resource. SFA 7 is the southernmost section of the fisheries located right off of Newfoundland. It is one of the smallest sections of the fishery (see Figure 2.) Table 1. Provides a comparison of the GOM fishery and the Eastern Canada fishery.

The GOM fishery is run under one regime for the area. In Eastern Canada, there are 7 main fisheries including the Nova Scotia Fishery, Labrador Fishery, and the Gulf of St. Lawrence Fishery (see Figure 1 for a map of the fisheries) (Perennia, 2024; Government of Canada, 2016). Also, right outside of the GOM exists Georges Bank which separates the GOM from the Atlantic Ocean. Georges Bank is shared between the US and Canada. This was decided in 1984 when the Eastern US-Canada Boundary line was drawn, officially dividing the fishing grounds between the US and Eastern Canada (Herbert, 1995). See Figure 3 for the boundaries.

Table 1. Comparison of the GOM Fishery and the Eastern Canada Fishery

	GOM Fishery	Eastern Canada Fishery
Main water contributors	Labrador Current and Gulf Stream	Labrador Current
Number of regimes	one	sixteen
Status of Northern Shrimp Fishery	Moratorium since 2014	Currently open for fishing
Year fishery opened	1930s	1970s
Number of regimes open	N/A	6 out of 7

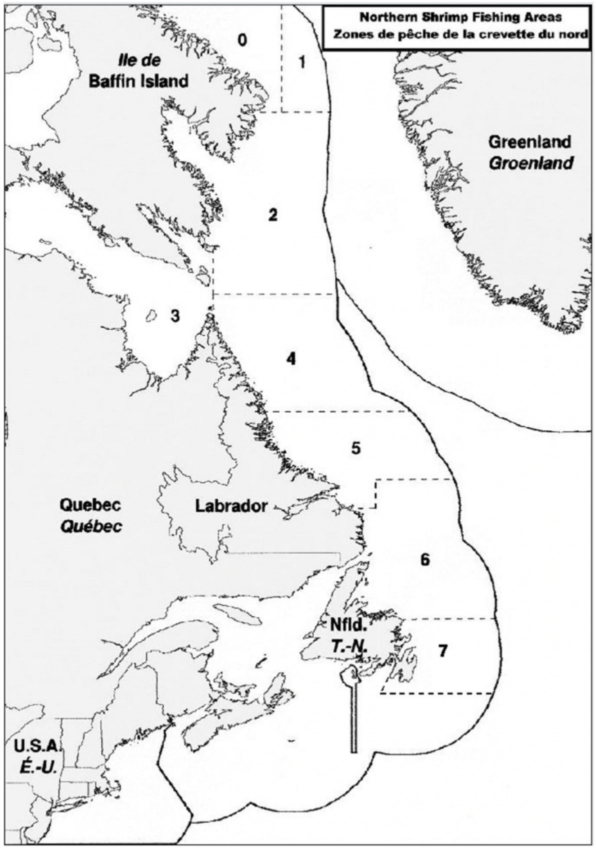

Figure 2. Shrimp fishing areas in the Northwest Atlantic off of Eastern Canada (DFO, 2018)

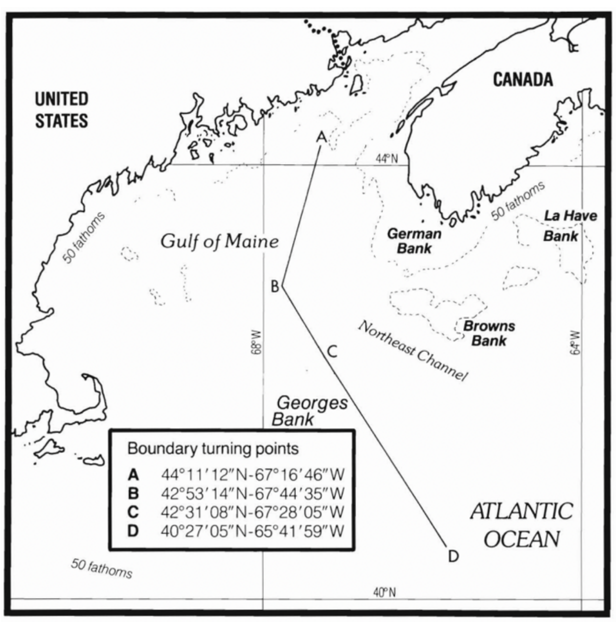

Figure 3. Map of GOM and Eastern Canada fishery boundaries (Herbert, 1995).

The topography of the GOM as well as the Eastern Canada fishery locations can have a large impact on currents and ocean circulation. There is one interconnected circulation system formed from Newfoundland, Labrador, the Gulf of St. Lawrence, the Scotian Shelf, and the GOM (Brickman et al., 2021). There is a northeast-southwest flow of water that characterizes the circulation region (Brickman et al., 2021). It is the confluence zone between the warm northeast-flowing Gulf Stream and the cold southwest-flowing Labrador Current (See Figure 4) (Loder et al., 1998). The annual cycle of circulation in the GOM is regulated by the surface heat flux of the interior shelf heating and exterior shelf cooling (Xue et al., 2000). There is more heating from April to June and more cooling from June to December (Xue et al., 2000). Han et al. (2008) created a model for Eastern Canada circulation and found that there is a southward flowing current along the Labrador shelf and that it is strong in the fall/winter and weak in the spring/summer. There is also a current from the Cabot Strait that is in phase with the Labrador current by also having a strong fall/winter flow and a weaker spring/summer flow (Wu et al., 2012). The current flows out of the Gulf of Saint Lawrence and along the inner Scotian shelf (Wu et al., 2012). Brickman et al. (2018), ran a model to look into the recent warming along the coast of Eastern Canada and in the GOM. The authors found that the warming begins in the Gulf Stream and the Labrador Current creating warmer, saltier eddies that are carried along deep channels at the shelf’s edge down through Canada and dumped into the GOM (Brickman et al., 2021).

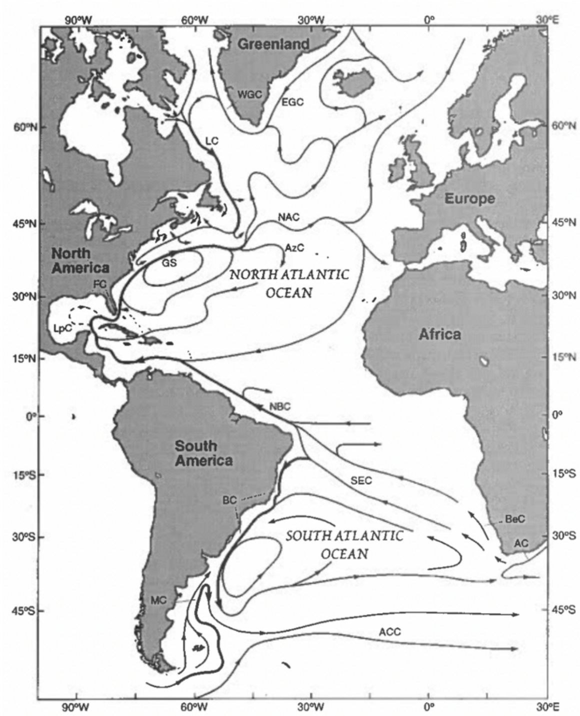

Figure 4. The current system through the Atlantic Ocean (Loder et al., 1998)

However, this warming water can harm Northern shrimp stock-recruitment relationships. Looking through a metapopulation level, very few studies have tried to understand the connection between the different northern shrimp stocks in each of the fisheries. Le Corre et al. (2020), investigate the relationship between the different northern shrimp fisheries and larval dispersal. Le Corre et al. (2020) conducted a study using a biophysical model to investigate larval dispersal among North Atlantic Fisheries Organization (NAFO) divisions. The authors also looked into its pelagic larval phase and its interannual variability. The authors found that there is a lot of larval connectivity between the fisheries driven by the ocean currents and circulation flowing between the Canadian and GOM shelves and that the highest abundance of adult shrimp was where most larvae settled (Le Corre et al., 2020). Le Corre et al. (2021), however further delved into the spatial distribution and variability of Northern shrimp based on their preferred depth and thermal habitat for larval dispersion. The authors projected that there would be a 4ºC gradual temperature increase in the seafloor by 2090 (Le Corre et al., 2021). This increase in temperature would cause the shrimp to move farther out, likely beyond the edge of the shelf for larval dispersion (Le Corre et al., 2021). Thus the larvae would be released off the edge of the shelf or get caught up in the ocean circulation (Le Corre et al., 2021). This would result in lower survival rates and recruitment of Northern Shrimp because larval survival is impossible off the edge of the shelf due to the deeper waters (Le Corre et al., 2021).

Climate change is impacting the GOM and Eastern Canada in several ways ranging from water temperature, and changes in pH, to changes in predator habitability. The ocean in the GOM has been warming 90% faster than the rest of the world's oceans, experiencing the two hottest summers in 2021 and 2022 (Mills et al., 2023). This warming is magnified in the GOM as compared to Eastern Canada. From the early 1980s through 2022, there has been a 0.6ºC increase in water temperature in Eastern Canada and the GOM per decade as compared to a 0.3ºC increase in other parts of the world (Thomas et al., 2017). There was also the 2012 marine heatwave anomaly that led to warmer temperatures and an almost immediate impact on the marine species distribution throughout the GOM (Mills et al., 2013). Many of their distributions changed with them moving farther out into the ocean and into the cooler waters (Mills et al., 2013). Possible drivers that could be contributing to this warming are the widening Gulf Stream, the warming Labrador Current, a more persistent North Atlantic Oscillation (NAO), and the fact that the GOM is a big, shallow body of water (Mills et al., 2013). In Eastern Canada, sea ice is necessary for phytoplankton production in the spring. Phytoplankton are one of Northern Shrimp's main sources of food. However, as the water warms, sea ice melts and phytoplankton production is reduced. Therefore there is less food available for the shrimp which can have a negative impact on shrimp survival, recruitment, and production. Many of the drivers for the Northern Shrimp population decline can also be attributed to increasing temperatures, decreasing pH and O_2, and increasing predator pressures (Chemel et al., 2020). Chemel et al. (2020) conducted a study on Northern shrimp that mimicked ocean conditions and found that shrimp survival decreased (68%) when the water temperature was higher or pH was lower. They also found that shrimp survival also decreased (37%) when they were exposed to hypoxia (Chemel et al., 2020). The introduction of new predators to the GOM and Eastern Canada is also a result of climate change. Richards and Hunter (2021) found that the increase in water temperature has allowed longfin squid to move into the GOM and prey on Northern Shrimp. The longfin squid hadn't previously been a predator of Northern Shrimp because there was no overlap in their locations, but now climate change has made it possible (R. A. Richards & Hunter, 2021).

The increasing water temperatures in the GOM and Eastern Canada can have both direct and indirect impacts on the Northern Shrimp populations. This paper aims to explore how the warmer waters have resulted in the decreasing shrimp population in the GOM and if that is likely to occur in the Eastern Canada fisheries as well. The fishery in the GOM shut down, however, the Eastern Canada fisheries have remained open despite the ever-decreasing Northern Shrimp population and recruitment. It is known that climate change is negatively impacting Northern shrimp populations through increased warming temperatures, but how this impact is different between Eastern Canada and the GOM remains enigmatic. To address this question, this paper will explore the direct and indirect effects of the warming waters in the GOM and Eastern Canada. Secondly, this paper will investigate the fisheries management of these populations and address any disagreements in the literature.

Analysis and Methods

Direct Impacts of Warming Water on Northern Shrimp: GOM

The waters in the GOM are rising rapidly which can be seen by more frequent temperature anomalies. It is also known that the Northern Shrimp population has been on the decline. Warmer water temperatures can have impacts on Northern Shrimp at the sea surface and at the sea bottom. The sea surface is where the shrimp spend their larvae stage, feeding and growing until they are able to mature into juveniles and move to the ocean floor to spend the rest of their lives. However, very little is known about how changes in the GOM sea surface and bottom temperatures have affected the Northern Shrimp populations directly. Some direct impacts could include egg survival, hatch timing, sex change timing, recruitment, and feeding conditions.

In shrimp populations, development, growth, and metabolism are all temperature-dependent (Pörtner, 2002). In the GOM, if water temperature increases, it can impact egg development and survival in the females. This was demonstrated by Brillon et al. (2005) who tested the impacts of temperature and food ration on females to see how it impacted egg survival, embryonic development, and larval conditions. Brillon et al. (2005) collected Northern Shrimp from St. Lawrence and put into tanks at 2ºC, 5ºC, or 8ºC to be monitored and removed females at random to be inspected. Brillon et al. (2005) found that the increase in temperature (8ºC as compared to 2ºC or 5ºC) led to more egg development but their survival was reduced. This was attributed to the conversion of yolk reserves in the developing embryos being heavily decreased at higher temperatures (Brillon et al., 2005). This demonstrates that at higher temperatures the females are spending more energy trying to develop their eggs, but this results in higher mortality as they become subject to other conditions. Also, the larvae that hatched at 2ºC and 5ºC were much larger and heavier than the larvae that hatched at 8ºC (Brillon et al., 2005). The larger and heavier eggs have a higher chance of success and survival through the larvae stage. The females held at 8ºC also had much lower energy reserves than those at the cooler temperatures (Brillon et al., 2005). However, the food ration didn't impact the female energy, egg characteristics, or their biochemical composition (Brillon et al., 2005). This demonstrates that the water temperature was the most impactful factor in shrimp survival during the egg development stage and that cooler temperatures result in a higher success rate.

Daoud et al. (2010) also conducted a study in aquaculture lab tanks looking at temperature impacts at 2ºC, 5ºC, and 8ºC. However, the authors instead looked at juvenile male and female shrimp and water temperatures impact on growth characteristics including intermolt period (IP), molt increment (MI) in size and mass, and tissue allocation (Daoud et al., 2010). The authors found significant variations in growth related to shrimp size and temperature (Daoud et al., 2010). The IP in days increased significantly when shrimp size increased (Daoud et al., 2010). However, the IP decreased when temperature increased, therefore they have an inverse relationship (Daoud et al., 2010). Therefore, the shrimp have shorter IP because they are in warmer water conditions and they are smaller because they move through their life stages faster.

Juveniles are more sensitive to temperature changes than adults and have very short IPs (Daoud et al., 2010). This suggests that temperatures encountered during the juvenile stage will heavily influence the growth trajectory and capability of the juvenile population (Daoud et al., 2010). With the IP decreasing, it results in the shrimp growing at a faster rate, which means their lifespan will be shorter (Daoud et al., 2010). The decreased IP also means that the shrimp will be smaller through each life stage because they will move through each stage without as much time to grow. The shorter IP demonstrates that the health of the shrimp is also essential as they will always be under warmer temperature stress (Daoud et al., 2010).

Chang et al. (2021) however, investigated the impact of body size on potential fecundity (PF), relative fecundity (RF), and egg size (ES) from a random sample of female shrimp with eggs within the GOM. PF and ES were found to be related to body size whereas RF was not (Chang et al., 2021). PF and RF were found to be positively correlated with bottom temperature so the environmental impacts observed could reflect the inshore migration of the females (Chang et al., 2021). The ES declined as body size increased and the larger females produced more eggs however those eggs produced smaller larvae with lower survival rates (Chang et al., 2021). So in conjunction, the increasing water temperature can shorten the intermolt period allowing the shrimp to grow larger, but these larger shrimp cannot produce as many viable larvae (Chang et al., 2021). This contradicts the findings by Daoud et al. (2010) that said that increased water temperature would result in smaller adult female shrimp because they go through intermolt periods faster. It should also be noted that Chang et al. (2021) only looked at the differences in temperature based on how close inshore they were so there wasn't as much temperature variation as what was seen in the research done by Daoud et al. (2010).

Richards (2012) looked into ocean temperature impacts on reproductive phenology from 1980-2011 and estimated the annual hatch by sampling commercial catches during the brooding and hatching periods. By putting these samples against the surface and bottom temperature anomalies, a shift was observed over time in that the timing of the hatch was earlier and the completion of the hatching period was later (Richards, 2012). This resulted in an overall longer hatch period (Richards, 2012). Richards (2012) found that all hatching metrics were related to water temperature and that these phenological shifts that were seen could be beneficial because they create a longer window of time for shrimp larvae to encounter good survival conditions. So the warming of the ocean waters could be beneficial to larvae survival but only to a certain extent (Richards, 2012). This is applicable because there are more phytoplankton available at slightly elevated temperatures as they thrive with more sun for photosynthesis. The Northern Shrimp are able to obtain more nutrients at slightly elevated temperatures but the warmer waters do also decrease overall fitness above a certain temperature the warm no longer benefits the phytoplankton (Richards, 2012). However, Richards et al. (2012) argued that this increase in temperature from 1968 to 2012 led to more variability in recruitment. This means that there were more fluctuations in recruitment, and they could especially be seen after a 1999 temperature shift (Richards, 2012). Richards (2012) noted that colder temperatures during the pelagic larval stage were associated with higher recruitment to the fishery and that there have been changes in the physical environment as well as other trophic levels that were associated with the temperature shift.

These papers demonstrate that there is a direct impact of warming ocean temperatures on the Northern Shrimp populations and they can be demonstrated by decreased egg survival, shorter IP, longer hatching periods, and lower recruitment. Some of the aspects of warming could be seen as beneficial, however, without egg survival or recruitment, the shorter IP and longer hatching periods become inconsequential.

Direct Impacts of Warming Water on Northern Shrimp: Eastern Canada

In Eastern Canada, these direct climate change temperature impacts are less prevalent than what is seen in the GOM due to the fact that they the water temperatures are lower than what is currently seen in the GOM. As previously mentioned, the GOM is warming faster than 90% of the other oceans (Mills et al., 2023). However, the water temperature is still increasing at close to the same rate as what is seen in the GOM (Mills et al., 2023). Brickman et al. (2021) found that the warming begins in Canada as the Gulf Stream and the Labrador Current creating warmer, saltier eddies that are carried along deep channels at the shelf's edge down through Canada and dumped into the GOM. However, the warming waters still impact the Northern Shrimp populations existing in Eastern Canada. As previously discussed by Le Corre et al. (2021), there is a projected increase in seafloor water temperatures by 4ºC by 2090. This increase in seafloor temperatures would make the Northern Shrimp habitat too hot and would result in the Northern Shrimp moving farther out into the ocean (Le Corre et al., 2021). This also means that female shrimp won't come as close to shore for larval dispersion so the larvae could be released off the continental shelf or get caught up in the ocean circulation effectively killing the larvae (Le Corre et al., 2021). As little as a 2º shift out towards the ocean increased the probability of the larvae being lost off the Canadian shelf by 2% (Hvid Ribergaard et al., 2004). However, the increase in water temperature doesn't just impact larval dispersion, it also results in a decreased egg-bearing period (Wieland, 2005). Chemel et al. (2020) conducted a study with Northern Shrimp collected from trawling in Quebec, Eastern Canada and being moved to tanks in a lab where they tested shrimp survival based on several factors including temperature (2, 6, and 10ºC). Much like the GOM, shrimp survival was found to be significantly lower as the temperature increased (Chemel et al., 2020). P.A. Koeller (2000) also finds that temperature is an important factor in shrimp survival thus impacting shrimp location. In this study, previous datasets on Northern Shrimp surveys, bathemetric information, and groundfish surveys Northern Shrimp were utilized and found that Northern Shrimp only inhabit relatively small locations on the Scotian Shelf despite the large area of suitable habitat (P.A. Koeller, 2000). This phenomenon was because those small areas were the only places with marginally suitable temperatures (P. A. Koeller, 2000). It was also determined that migration patterns on the Scotian Shelf are mainly impacted by temperature regime differences (P. A. Koeller, 2000). Overall, the warming ocean waters result in larval dispersion moving farther out into the ocean, as well as shrimp population migration to cooler, more suitable temperatures.

In the Gulf of Saint Lawrence, the biomass of shrimp species increased from the late 1980s to the mid-2000s (Tamdrari et al., 2018). During a point of stability from 2004 to 2015, Tamdrari et al. (2018) utilized the trawl survey to find a strong association between species assemblages and bottom water temperatures and depth. This signified that there are narrow temperature associations so the northern shrimp populations are more susceptible to ocean warming. P. Koeller et al. (2000) discuss the possible impact of temperature on the Northern Shrimp sex changes that occur around age 3-4. The transition occurs at different sizes and ages and the drivers remain an anomaly (P. Koeller et al., 2000). The authors found that population density and temperature both influenced shrimp size when they transitioned (P. Koeller et al. 2000). Temperature was especially important at low population densities as a determinant of growth (P. Koeller et al. 2000). (Wieland, 2004) found that length at sex transition and mean length of females to both have decreased since the 1990s as mean bottom temperature has increased by 1.9ºC. This demonstrates that with elevated temperatures the size of the shrimp will continue to decrease which results in lower success rates in regards to survival and reproduction.

All of these studies point to the importance of temperature in Northern Shrimp viability. The GOM is currently feeling the impacts of warmer temperatures as the likelihood of Northern Shrimp persistence decreases. Eastern Canada has demonstrated that it likely will feel the impacts of the warmer temperatures soon as water temperature is such an important factor in Northern shrimp population location, sex change, and larvae dispersal. These warmer waters result in shrimp population migration which can negatively impact the overall recruitment because shrimp won't immigrate into the area if the water is too warm and outside their typical range. All these studies show us that there is a large relationship between temperature and Northern Shrimp populations.

Indirect Impacts of Warming Waters on Northern Shrimp: GOM

In addition to the direct effects of warming, the increasing ocean water temperature has secondhand impacts on shrimp through changes in factors like predation, parasites, pH, and more. Climate models predict a 0.3 to 0.5 decrease in pH by the end of this century (Arnberg et al., 2013). However, warming and ocean acidification occur conjointly so Arnberg et al. (2013) investigated the impact of decreasing pH in concert with increasing temperature on Northern Shrimp. Arnberg et al. (2013) collected Northern Shrimp with a trawl in Norway's and transported them to a lab located in Canada where they were randomly put into tanks of differing pH and temperature. Arnberg et al (2013) investigated the hatching timing and success, and the embryo development, survival, and growth of the Northern Shrimp due to the decreased pH and increased temperature. The results showed that temperature had a larger effect on embryonic development than pH (Arnberg et al., 2013). Decreased pH caused a significant delay in larval development, but that was only true at the colder temperatures (Arnberg et al., 2013). Therefore, pH is an important aspect of Northern Shrimp success but it likely is not one of the leading factors behind the population decrease.

Chang et al (2021) investigated the impacts of parasite-infected northern shrimp eggs due to increased temperature. Chang et al (2021) collected Northern Shrimp with a trawl in the GOM where the shrimp were then frozen to be transported to shore so that size and fecundity could be measured in a lab. "White eggs" are shrimp eggs that have been infected by a parasite which makes them nonviable and subsequently ruins the recruitment potential (Chang et al., 2021). White eggs have been an issue for a long time, but the increasing temperature has led to an increase in the number of infected females (Chang et al., 2021).

The probability of an infected female was high in the GOM (74%), but the probability of white eggs in an infected female remained low (<5%) (Chang et al., 2021). However, the average of both infected females and the proportion of white eggs per female have increased since the 1960s when the bottom temperatures were cooler (Chang et al., 2021). As the quantity of infected females increases, the overall likelihood of there being a white egg also increases because females that aren't infected won't produce a white egg (Chang et al., 2021). Therefore the rising temperatures are increasing the parasite population and viability of a female getting infected (Chang et al., 2021).

However, rising temperatures don't only affect the feasibility of parasites, the warmer temperatures also allow for predator distributions to change and for new predators to move into Northern Shrimp habitats. Hunter et al. (2021) utilized previous datasets from trawling in the GOM to investigate the large Northern Shrimp population decline that occurred directly after the 2012 heatwave and deemed it to be due to the presence of a new predator: Longfin Squid. Longfin Squid demonstrated a population peak around the same time as the Northern Shrimp and they are known to be an opportunistic species in that they will eat anything from fish to crustaceans (Hunter et al., 2021). Hunter et al. (2021) hypothesized that the warmer temperatures allowed for the Longfin Squid to expand its distribution into the GOM leading to overlap and the subsequent consumption of the Northern Shrimp. Therefore, an increase in water temperature in the GOM leads to an increase in predators which likely results in a decrease in the shrimp population.

Indirect Impacts of Warming Water on Northern Shrimp: Eastern Canada

The secondhand warming impacts are not exclusive to the GOM. These impacts can be felt in Eastern Canada too as shifts predator presence, and more alter the success and survival of Northern Shrimp. Lilly et al. (2000) utilized previous datasets and indices for Northern Shrimp and Cod populations to examine the impact of the collapse in the biomass of Cod on the Northern Shrimp population. The collapse occurred in the late 1980s and there was a subsequent increase in Northern Shrimp populations (Lilly et al., 2000). Lilly et al. (2000) determined that that larger increase in shrimp biomass in the 1990s was at least partially related to the collapse of the Cod. Cod collapse was attributed to the warming water temperatures making Cod recovery and survival harder (Hanna et al., 2008). This release of predation pressure due to the increasing temperature might be true for Cod at that time, but it also, similarly to the GOM allows for the opportunity for new predators to come in. It should also be noted that Planque and Frédou (1999) found that Cod stock recruitment is favored by increasing temperatures, thus more predation could occur in warm periods in the future.

Burns (2018) evaluated the impact of warming waters on the spring phytoplankton production. Phytoplankton is a large food source for shrimp so their presence is essential for Northern Shrimp survival. Sea ice dynamics are a large driver of spring phytoplankton production and without the phytoplankton, shrimp recruitment and production rates will decrease (Burns, 2018). However, Burns (2018) noted that there is a decrease in sea ice due to the warmer waters thus leading to lower shrimp recruitment and production. Le Corre et al. (2021) argued that the warming water temperatures will likely change the locations of suitable shrimp habitats and make the locations that are on the continental shelf smaller. The suitable habitat distribution is associated with changes in ocean circulation patterns and temperature (Le Corre et al., 2021). Locations that used to be deemed a suitable habitat have now become too warm, effectively pushing the shrimp populations out to cooler waters (Le Corre et al., 2021).

In both the GOM and Eastern Canada, the warming waters are having secondhand impacts on Northern Shrimp populations. This can be seen through predator distribution, pH, parasite infection rates, prey availability changes, and habitat viability. Although predator distribution can potentially have a positive impact through predators moving out of the Northern Shrimp range, the overall secondhand impacts of warmer ocean waters are negative on the shrimp populations.

Fishing and Fisheries

The Northern Shrimp population in the GOM are at an all-time low due to recruitment and spawning-stock biomass (SSB) decreasing (ASMFC, 2021). As mentioned in the introduction, a moratorium was put in place in 2014 to try and minimize the impact of fishing on the diminishing Northern Shrimp populations. A benchmark assessment was conducted in both 2018 and 2021 using a traffic-light analysis and catch-at-length model to analyze the Northern Shrimp population stock status. The traffic-light analysis indicates levels of concern for the stock based on commercial landings (green means the stock is healthy, yellow means the stock is at risk, and red means the stock is very unhealthy). The catch-at-length model utilizes a stocks maximum sustainable yield to estimate the stocks current size, harvest rate which can inform management. The results from these analyses and models found that abundance, recruitment, and SSB have all decreased and remain in poor condition (ASMFC, 2021). The authors also examined the predator pressure index and found that it has been above the overall time series median since 2006 (ASMFC, 2021). In 2021 the SSB was estimated to be 887 mt which is still well below the time series (1984-2021) median SSB of 4,037 mt (ASMFC, 2021). All projections determined Northern Shrimp SSB to decrease further through 2026 with a possible stabilization of around 400 mt (ASMFC, 2021). Recruitment has consistently been low and that continued through 2021 (ASMFC, 2021). The 2021 stock assessment determined that the stock is in very poor condition and likely won't recover soon so the moratorium should be continued indefinitely (ASMFC, 2021). Fishing shrimp when their levels are so depleted would be unsustainable and could further negatively impact their biology and status (ASMFC, 2021). The catch-at-length total biomass from 1984 to 2021 can be seen in Figure 5 below.

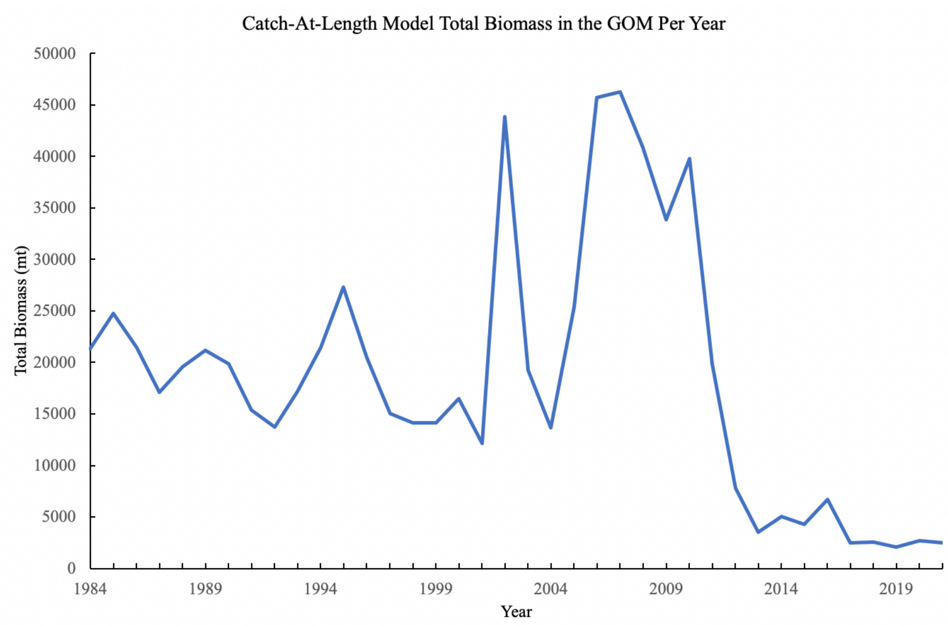

Figure 5. Total Biomass data for Northern Shrimp in the GOM from 1984-2021 as found through the Catch-At-Length model. Data from ASMFC.

Although commercial fishing in the GOM hasn't occurred since the 2014 moratorium, research trips have been conducted to obtain information on the shrimp population regarding recovery. Sea Surface Temperature (SST) from February to March and ocean bottom temperature in the summer were also measured. The Atlantic State Marine Fisheries Commission utilized the predation pressure index (PPI) to analyze the impact of predators on Northern Shrimp populations . The PPI determined that predation pressure partially contributed to the shrimp stock collapse. This is thought to be due to the new presence of Longfin Squid that heavily prey upon Northern Shrimp and have few predators of their own allowing their population to thrive and grow.

The Atlantic State Marine Fisheries Commission also used the traffic light analysis which uses abundance, fishery performance, and environmental trends to determine resource conditions and shrimp stock status. The data collected through 2021 indicated that the stock status continued to decline with decreasing resource conditions. All results demonstrated that the environmental and biological conditions for Northern Shrimp stock survival are diminishing.

Finally, the Atlantic State Marine Fisheries Commission used the Catch-at-Length model to help determine that total abundance and SSB remained at low levels from 2018 to 2021 and that the SSB is still well below the overall time series median. The total shrimp removals from 1985 to 2021 in the Northeast can be seen in Figure 6 below.

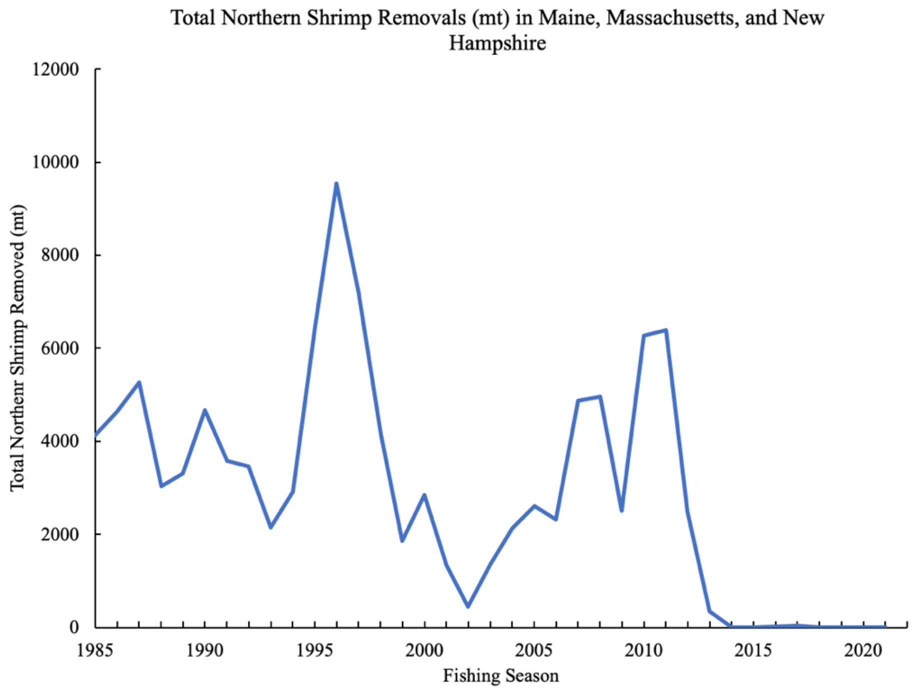

Figure 6. Landing data from Northern Shrimp in Maine, Massachusetts, and New Hampshire from 1985 to 2021. Fishing methods included traps and trawls. Data from (2021 assessment report PDF).

Eastern Canada is beginning to experience the dropping Northern Shrimp populations the GOM has been experiencing since 2014. A 2021/2022 assessment report was conducted for the fishing year and found that 8,359t of shrimp were caught in the Eastern zone and 1,248t in the Western zone (DFO, 208). This is 74% of the Total Allowable Catch (TAC) in the Eastern zone and 24% of the TAC for the Western Zone (DFO, 2018). The TAC can inform researchers about the biomass. In both assessment zones in 2021, despite being well below the TAC, the biomass index and female SSB decreased substantially and are now below their time series mean (DFO, 208). The exploitation rate is also above the time series mean in both zones. However, it was deemed that the stock was still within the Healthy Zone of the framework but there is the possibility of the population moving into the Cautious Zone (DFO, 2018). Figure 6 graphs the landings data for both assessment zones from 1990 to 2021.

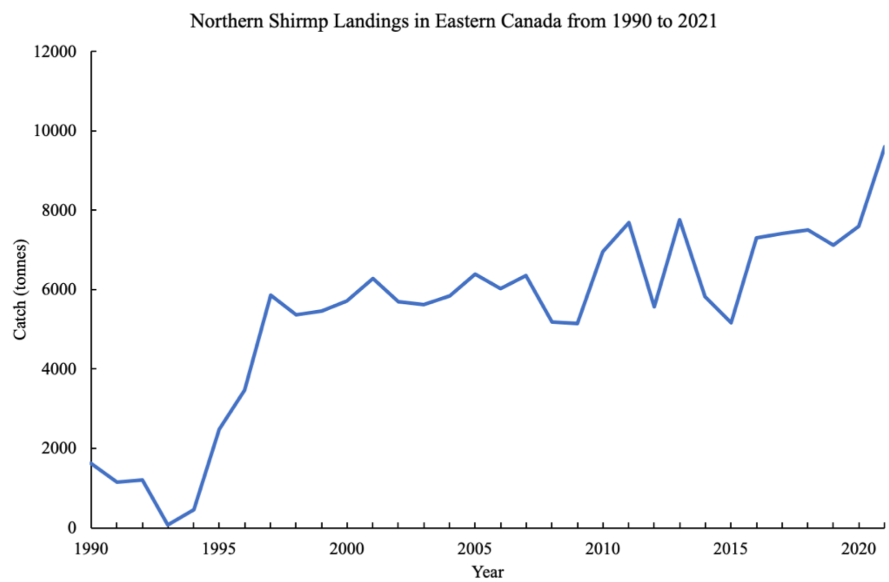

Figure 6. Graph of the Northern Shrimp landings data between both the Eastern and the Western Assessment zones from 1990 to 2021. Data from the Department of Fisheries and Oceans Canada.

All of the data that has been presented for both the GOM and Eastern Canada shows that fisheries have been within the TAC for each year and not much overfishing has occurred. In the GOM, no commercial fishing has occurred for almost ten years. However, the Northern Shrimp populations keep declining in both locations and recruitment and SSB are failing. This demonstrates that the fisheries haven't influenced the population collapse. It instead demonstrates that the population collapse was likely driven by another factor such as the warming water conditions. Therefore the literature previously listed in regards to warming waters could be a significant reason for the dwindling of the Northern Shrimp populations; but it could also be the answer to the problem.

Contradictions in the Literature

The research presented throughout this paper demonstrates that there is a profound effect of climate change on the Northern shrimp populations both directly and indirectly. However, there is some disagreement between the conclusions that are important to discuss. Most of the research agrees that climate change and warming waters has a negative effect on

Northern Shrimp populations, however, some studies find that the warming waters can actually have positive impacts. These misalignments in the literature need to be addressed.

Daoud et al. (2010) found that the increasing temperature shortened the intermolt period (IP). With the IP decreasing, it facilitates more opportunity for the shrimp to grow at a faster rate but to a smaller final size. This faster growth was also associated with higher sensitivity to temperature changes and the health of the shrimp is essential because the temperatures encountered in the juvenile stage can heavily influence the success and trajectory of the population (Daoud et al., 2010). Chang et al (2021) however found that with the shorter IP, there will be the presence of larger females and that these larger females will produce more eggs. However, the eggs will produce smaller larvae with lower survival rates (Chang et al., 2021). Therefore there is a misalignment in the research about whether the warming waters causing the shorter IP is resulting in larger or smaller females. It can be inferred that it is a net negative outcome due to the lower survival rates of the larvae, but does size impact the overall success of the larvae being produced?

Richards (2012) also found some good news in the warming waters in that it resulted in an overall longer hatch period. The longer hatch period facilitates the opportunity for the larvae to encounter good survival conditions (Richards, 2012). However, these findings are counteracted by Le Corre et al. (2021) who demonstrate that the increase in temperature will change the location of viable habitat to farther out in the ocean, possibly off the continental shelf. This will decrease the possibility of survival for the eggs to even reach the hatching period because they will be lost off the continental shelf or caught up in the ocean circulation and survival rates will plummet (Le Corre et al., 2021). However, the gap in the research here is the rate of egg loss off the continental shelf and if the larvae are also moving out into the cooler waters during the hatch period. If so, how is this impacting the larvae population levels?

Another disagreement in the research can be seen by the presence of new predators and the omission of old ones. Lilly et al. (2000) found a rise in shrimp populations after the collapse of the Cod populations in the 1980s. It was interpreted to be an indirect impact of the warming waters as the increase in temperature likely made the water unlivable for the Cod (Lilly et al., 2000). Due to Cod being one of Northern Shrimp's main predators it was extremely beneficial to shrimp population survival and allowed for a population boom (Lilly et al., 2000). Hunter et al. (2021) however looked into this increase in temperature allowing for new predators to enter the Northern Shrimp habitat. The Longfin Squid's habitat increased into the Northern Shrimp waters after the 2021 heatwave and it became one of the shrimp's largest predators (Hunter et al., 2021). The GOM fishery report even recorded a plummet in Northern Shrimp populations after the Longfin Squid's arrival (2021 GOM stock assessment PDF) See Table 2. for a summary of the contradictions in the literature.

But these two studies leave a gap in the literature in regards to how the new arrival and departure of predators and it begs the question: what is the rate that old predators are leaving and new ones are coming in? Can any more research be done about how the increase in Cod recruitment levels with warmer waters will impact the Shrimp population? Has there been any return of the Cod population after the collapse in the 1980s? Has there been any recession in the Longfin Squid population after their arrival in 2012?

Table 2. The main contradictions in the literature about the direct and indirect impacts of water temperature on Northern Shrimp.

Size and egg viability	Daoud et al., (2010) said that increased temperature decreases female shrimp size as well as egg viability.	Chang et al. (2021) found that increased water temperature increases female shrimp size but lowers egg survival.
Larvae finding viable habitat	Richards (2012) found an increase in water temperature results in increased time for larvae to find a viable habitat	Le Corre et al. (2021) determined that increased water temperature results in larvae moving farther offshore to find a habitat and falling off the continental shelf
Predator pressure	Lilly et al. (2000) determined that predator pressure decreased and allowed shrimp to thrive after Cod populations decreased	Hunter et al. (2021) said that the introduction of the Longfin Squid resulted in increased predator pressure on shrimp, making their populations fall

Discussion and Conclusion

Climate change is having impacts on the Northern Shrimp habitats and populations. This can be seen by the research presented above as well as the current status of the fisheries that demonstrate the decline in SSB and recruitment. In both the GOM and Eastern Canada, climate change can be seen through the warming ocean water temperatures. These warmer temperatures can have direct impacts on the Northern Shrimp populations. In the GOM this was demonstrated through decreased egg development and survival, changes in growth characteristics, decreased fecundity, longer hatching periods, and lower recruitment. In Eastern Canada, the direct impact of the warmer waters included increased egg loss off the continental shelf, decreased survival, fewer locations for suitable habitat, and earlier sex transition. The main indirect climate impacts on the Northern Shrimp in the GOM include pH changes that impact larval development, increased parasites that infect females, changes in predator distribution, and the introduction of new predators. Finally, in Eastern Canada, there are secondary impacts of the warming waters that include changes in predator distribution and recruitment, less ice for phytoplankton production, and reduced habitat viability.

Although there are some positives in the increasing temperatures, the net impact can be seen to be negative through the diminishing population size in the fishery in Eastern Canada and the nonexistence of the Northern Shrimp fishery in the GOM. The fishery in Eastern Canada however, has not slowed its fishing or Total Allowable Catch (TAC) and this decision could have negative impacts as the population and recruitment continues to decline. The Northern Shrimp populations have been dwindling and are at risk of local extinction. This will likely persist even if all fishing stops in Eastern Canada and continues to not exist in the GOM because the GOM has had a moratorium in place for nearly ten years but yet very little recovery has been made in both SSB and recruitment and they just continue to decrease. This is true and even magnified in Eastern Canada because there hasn’t been a stop to the fishery but the TAC has been decreasing. However, the SSB and recruitment levels are dropping extremely quickly in Eastern Canada and run the risk of total depletion of the population.

The GOM 2021 stock assessment addresses some opportunities for improvement including improvement on the modeling, sampling, and biological understanding of the Northern Shrimp species (2021 GOM stock assessment PDF). These suggestions for improvement can be divided into fisheries-dependent improvement and fisheries-independent research contingent on if the moratorium is lifted or not (2021 GOM stock assessment PDF). The fisheries-dependent goals for improvement include evaluating trawl and trapping methodologies and determining levels of by-catch in the fisheries (2021 GOM stock assessment PDF). They also recommend continued sea and port Research-set-aside (RSA) sampling throughout the winter so that length-frequency can be updated (2021 GOM stock assessment PDF). As for fisheries-independent research, it was recommended that summer sampling keeps occurring, as well as identifying shrimp habitat or lack thereof (2021 GOM stock assessment PDF). The habitat location was determined to be less significant but it is known that the population is shrinking (2021 GOM stock assessment PDF). Finally, the last opportunity for improvement mentioned was the lack of research into size-based relationships for maturity and fecundity (2021 GOM stock assessment PDF).

The Eastern Canada fisheries also suggests some possible improvement recommendations in their fishery network including incorporating more cost-effective harvesting strategies. This could help promote responsibility in compliance with objective-oriented conservation and management. Also the promotion of a harvest level that meets marketing requirements and could help stabilize the industry infrastructure. This could be seen through the TAC as some sections of the Eastern Canadian fishery get shut down for the season because population levels are too low but it will benefit the fishery in the future assuming the population is able to recover. It was recommended to keep the TACs in levels where the stocks can stay or return to the Healthy Zone. The mitigation of fishing on the shrimp population and other groundfish species in the area could also benefit shrimp species as it will allow for better recruitment and larvae survival. Some strategies are recommended to be implemented to allow for the continued persistence of the Northern Shrimp species and fishery in Eastern Canada. One strategy is to not allow any new access to the fishery and that there should be a balance between fleet capacity and resource availability. There is also the suggestion to continue to communicate with Indigenous Peoples and work with them to co-manage the resource. There was also the recommendation of creating an annual Northern Shrimp Advisory Committee (NSAC) that could help with assessing stock and recruitment levels and advise increases or decreases in fishing (DFO, 2018).

There is a lot of information known about the impacts of climate change on the Northern Shrimp species and their respective fisheries in the GOM and Eastern Canada, but there is a gap in knowledge in how the two fisheries and locations tie together. Is the GOM foreshadowing events that are likely to occur in Eastern Canada? If so how can it be mitigated and how can the above research help prevent the disappearance of the species in

Eastern Canada? Are there any actions that can mitigate the lowering of SSB and recruitment? It is shown through the GOM fishery that shutting down the fishery once the population levels are super low won't be very beneficial, but could the population recover if commercial fishing is stopped while the shrimp levels aren't too low? Future research may be able to address these questions and find a solution to the ever-decreasing Northern Shrimp populations.

There are obvious differences between the GOM and Eastern Canada Northern Shrimp populations, however it appears to all be due to timing. Northern Shrimp in warmer waters has shown a resulting decrease in population size and recruitment levels. The GOM Northern Shrimp levels are diminutive and that is highly attributed to direct and indirect warming of the ocean. Eastern Canada Northern Shrimp population levels appear to be decreasing as well due to many of the same factors. The GOM could be a preview of the challenges that Eastern Canada is going to face soon unless new management and research precautions are not taken soon.

CHAPTER TWO:

The Impacts and Mechanisms of Warming Water Temperatures on Northern Shrimp (*Pandalus borealis*) Populations in the Gulf of Maine and Implications for the Scotian Shelf and Other Locations

Introduction

Northern Shrimp (*Pandalus borealis*) are a very common part of seafood dishes ranging from shrimp rolls and shrimp chowder to even shrimp cocktails. Shrimp are the most commonly eaten sea species with each person eating about 5.9 pound of shrimp per year. In, Maine shrimp were accessible and have been a key fishery since the 1930s. But this is no longer the case in Maine after the year 2013. The Northern Shrimp population, once a key commercial fishery and species, experienced a 90% population crash in the Gulf of Maine (GOM here forward) dropping from 39,774.6 mt in 2010 to 3,534.8 mt in 2013 and has still not recovered. Continued failure in recruitment as well as rising ocean temperatures leaves the Northern Shrimp population at dwindling levels. To try and combat this issue, a moratorium was placed on the Northern Shrimp Fishery, but very little recovery has been seen as the spawning stock biomass (SSB) staying around 2,000 mt and total biomass continues to decline below 4,000 mt.

Northern Shrimp (*Pandalus borealis)* are located in the oceans along the continental shelf of the Northern Hemisphere. They live and spawn in the cold waters of the North Pacific, North Atlantic, and Arctic Oceans (NOAA, 2024). More specifically they are found along the coasts of Iceland, Norway, and Japan, as well as ranging from Alaska down to Washington, and Greenland down to the GOM (Clark et al., 2000). However, the warming water temperatures have resulted in Northern Shrimp populations to decrease in the GOM. But this is likely not an isolated incident as warming ocean temperatures are occurring around the world. The Eastern Scotian Shelf, located in Canada, just Northeast of the GOM, could be the next fishery that is impacted by the warming waters and decreasing Northern Shrimp populations.

Northern shrimp are a very important part of aquatic ecosystems because they act as both predators and prey (NOAA, 2024). They prey on phytoplankton, zooplankton, and other small bottom-dwelling invertebrates and are a key source of food for many species including Longfin Squid, Redfish, Cod, Silver Hake, and White Hake (NOAA, 2024). Northern shrimp are crustaceans with a red coloring and translucent shells ranging in size from 2 to 4 inches in length (NOAA, 2024). They are nektons that can propel themselves through the ocean utilizing their tails pleopod (NOAA, 2024). Northern shrimp are benthic species and they tend to live in muddy bottom environments in depths ranging from 30 to 1,000 feet (NOAA, 2024). They thrive in cold water environments ranging from -1º to 8º C (NOAA, 2024).

Females begin spawning in July by pushing their eggs out onto their abdomen to get fertilized by males (NOAA, 2024). In late fall and early winter months, females move closer to shore and release their eggs before moving back out into deeper and colder waters (NOAA, 2024). The larvae are pelagic and remain nearshore for the first year until the juveniles move out into cooler waters (NOAA, 2024). The juveniles begin as male shrimp because Northern shrimp are protandrous hermaphrodites meaning that they begin their life as males and then turn into females as they mature (NOAA, 2024). Therefore, juveniles become male at 2 and can mate at 2.5 before transitioning to females between ages 3 and 4 and spawn between ages 3.5 and 4.5 (NOAA, 2024). Females can reproduce a second time but mortality increases (NOAA, 2024). Stage transition, however, takes a lot of energy for the shrimp especially for sex transition. Therefore, the shrimp become extremely vulnerable to outside conditions (such as temperature) during transition due to the lack of energy (Stickney and Perkins, 1977).

Northern shrimp are typically caught in the winter due to the egg-bearing females being closer to shore in the warmer waters for their eggs to be released (NOAA, 2024). Otter trawls are typically used to harvest shrimp (NOAA, 2024). Otter trawls are bottom-fishing gear that have heavy plates or otter boards that weigh down either side of the trawl as floats and headropes keep the mouth of the trawl open. They are dragged forward and scrape the muddy, soft-bottom floor to pick up any of the shrimp living down there (NOAA, 2024). There is minimal impact on the habitat due to the muddy seafloor not having much structure as well as the trawl creating more drag so the trawlers can't move very quickly over the habitat (NOAA, 2024). Bycatch is limited (~2%) as the fishermen target the specific habitat where shrimp will be and only target the seafloor (NOAA, 2024). There also is a minimum mesh size to prevent any male shrimp from getting caught (NOAA, 2024). This occurs because the larger mesh will allow the smaller, male shrimp to escape out of the holes in the mesh. They also use finfish excluders and size sorting devices to prevent the bycatch of groundfish as well (NOAA, 2024). The Northern shrimp stock is currently overfished meaning that the biomass of the stock is extremely low. The stock, however, is not subject to overfishing, meaning that the proportion of shrimp caught is less than the sustainable yield. This can be attributed to the moratorium being put in place on the fishery (NOAA, 2024).

The moratorium was put into place on the GOM Northern Shrimp fishery in response to the collapse of the fishery in 2013. This means that no fishing for Northern shrimp can be done anywhere within the GOM. It was determined that the Northern shrimp population was too low to be fishing sustainably so the fishery had to be shut down until the population could recover. Since 2013, Northern shrimp abundance has been monitored by the joint State-Federal summer shrimp survey which is run by the Atlantic States Marine Fishery Commission (ASMFC). The ASMFC also provides an annual stock assessment to fishery managers (NOAA, 2024).

The Northern Shrimp fishery began in the Northeastern United States in the 1930s with minimal landings and efforts (Clark et al., 2000). Up until the late 1960s, the fishery mainly operated inshore but it expanded to offshore in the late 1960s, bringing the peak landings up to 12,800 metric tonnes (Clark et al., 2000). Inshore fishing includes state waters that are 0-3 miles away from the coastline and offshore fishing are 3-200 miles away from the coastline (Schreiber, 2014). However, in the 1970s Northern shrimp recruitment plummeted, resulting in fishery landings dropping (Clark et al., 2000). This decline in recruitment could be attributed to the collapse of the Silver Hake fishery which resulted in a lot of fishermen changing to the shrimp fishery (Charleson, 2020). The number of boats in the shrimp fishery rose from 102 in 1964 to over 300 in 1970 (Charleson, 2020). The fishery was temporarily shut down in 1978 due to the stock collapse but slowly began to recover and was reopened in 1979. The fishery reached stability of around 3,000-4,000 metric tonnes per year in the early 1990s which was about 17% of the Northern shrimp global harvest (Clark et al., 2000). In 1996, there was another peak in Northern shrimp landings before the population dropped (Clark et al., 2000). Again, the population slowly began recovering up until the large population collapse in 2014 (Clark et al., 2000). In the four years building up to the 2014 collapse, the fishery had to be shut down early due to commercial fishermen exceeding the catch limit (Clark et al., 2000). In both the 1970s and 2014 the shrimp population collapse could be partially attributed to overfishing or large influx in fishing resulting in overfishing. A moratorium was put into place which banned fishing and harvesting of Northern shrimp (Clark et al., 2000). This aimed to allow for possible population growth and recovery in the population and recruitment but very little has been noted since the 2014 moratorium was put in place (Clark et al., 2000). Recruitment is dependent on spawning stock biomass (SSB) and ocean temperatures, neither of which have improved since the collapse (Clark et al., 2000).

The waters of the GOM are warming rapidly and at a rate higher than any other oceanic body of water. The GOM experienced its warmest ten years from 2013 to 2023 increasing over 0.5ºC. The GOM is part of the same interconnected sea shelf including the Labrador Shelf, the Gulf of Saint Lawrence, and the Scotian Shelf (Pershing et al., 2021). Within this region, just off the edge of the shelf is also the location of where the cold Labrador Current intercepts the warm Gulf Stream (Pershing et al., 2021). The Labrador Current circulates southwest and acts as the confluence zone to the northeast-flowing Gulf Stream (Pershing et al., 2021). The mixing waters circulate into the GOM where they get trapped by the higher topography of Georges Bank (Pershing et al., 2021). Amaya et al., (2023) determined that strong tidal mixing or possible advection by the Labrador Current could be associated with bottom temperature variability. Therefore, if there is any variability in the Labrador Current or tidal mixing it can be extremely impactful on the temperature in the GOM and can result in possible temperature anomalies or even marine heat waves (MHW).

Marine heat waves (MHW) are a more intense version of a temperature anomaly where the sea temperature deviates from the average temperature by upwards of 1ºC. MHW can occur at the sea surface or at the sea bottom. Amaya et al. (2023) found that MHW are heavily influenced by bottom depth, impacting both MHW duration and intensity. This is important due to the GOM's varying geomorphology as it contains both deep basins as well as shallow banks which means that MHW could have different impacts depending on location within the GOM. Amaya et al. (2023) determined that bottom MHW can occur separately from surface MHW and typically last longer, and at a higher intensity than surface MHW. Amaya et al. (2023) identifies that a possible reason for bottom MHW persisting longer than surface MHW is because the bottom temperature isn’t impacted by atmospheric turbulent heat fluxes because the ocean bottom is a highly insulated system. This is important because Northern shrimp tend to live on the ocean floor and any shifts in bottom temperature can have a large impact on demersal or benthic species.

The GOM has been warming heavily for the past decade, making way for huge shifts in aquatic ecosystems and organisms occupying its waters. The potential marine heat waves and definite temperature anomalies have left lasting impacts on many species populations including the GOM Northern Shrimp. There are direct and indirect impacts of the warming waters on the Northern Shrimp that have caused their populations to decrease and not be successfully rebuilt or repopulated.

Direct effects of the warming of the GOM include egg survival, hatch timing, sex-change timing, recruitment, and feeding conditions. Brillon et al. (2005) found that larvae that hatch at lower temperatures tend to be larger which is likely correlated with higher survival rates. This can then be related to the Intermolt Period (IP) that the shrimp go through which is shortened when temperatures are higher (Daoud et al., 2010). If the shrimp are smaller when they go through IP as well as sex transition, it can have negative effects on fecundity as well as survival because they are at a higher risk of health struggles if the water conditions aren't cool (Charleson, 2020). Fecundity and egg size were determined to be directly correlated with the warming waters because fecundity decreases with increasing temperature (Charleson, 2020). This is due to the size-at-sex-transition which has an inverse relationship with water temperature meaning that as water temperature increases Shumway et al. (1985) determined that the size-at-sex-transition decreases. However, Chang et al. (2021), found that fecundity is positively correlated with bottom temperature, but that the temperature has not breached the 10ºC threshold where shrimp can no longer survive. Richards et al. (2012) also determined that the warming waters had a direct impact on the variability of recruitment meaning that Northern Shrimp recruitment became extremely variable in response to warmer GOM waters. Overall, many studies have found and determined that the warmer waters in the GOM have had differing negative impacts on the population whether that be through individual growth, egg development and production, or recruitment.

The warming water temperatures can also have many negative indirect impacts on Northern Shrimp populations whether that be through changing pH, increased parasite populations, new predators, and decreased food availability. Arnberg et al. (2013) found that the increasing water temperatures cause shrimp to hatch earlier and have lower survival rates and that, along with changes in pH, resulted in larval development occurring much slower.

Therefore, the warmer waters in conjunction with changing pH cause the shrimp populations to be unable to develop before hatching causing survival rates to be much lower. Parasite populations are also increasing with the warming waters, especially the parasite that causes “white eggs". Chang et al. (2021) determined that warmer waters increased the number of infected females, thus increasing the number of non-viable “white eggs” produced. These “white eggs" can have a profound impact on the Northern Shrimp population as they aren’t adding to recruitment but they are utilizing nutrients by the female that produces it and makes the females more susceptible to other hazards due to their unnecessary overuse of energy (Chang et al., 2021). However, the warming waters are not only causing parasite populations to increase, but it is also allowing new predators to enter the GOM as their distribution changes. This is the case for the Longfin Squid, a species that used to not be able to survive in the GOM due to the cold waters but now that the water is warmer, the population can live and feed on Northern Shrimp (Hunter et al., 2021). This changing of population distribution isn’t only true for the new Longfin Squid predator, but it is also the case for Northern Shrimp prey; phytoplankton. Burns (2018) looked into decreasing phytoplankton populations in Eastern Canada as a result of a decrease in sea ice. The smaller quantity of sea ice has resulted in a less suitable habitat for phytoplankton production and survival which is likely the case in the GOM as well as the waters continue to warm. Overall, there are indirect impacts of the warming ocean waters that have just as many consequences as the direct effects.

This study will explore the possibility of warming ocean waters impacting different biological variables (total biomass, spawning stock biomass (SSB), and recruitment) in both the GOM and the Eastern Scotian Shelf off the coast of Canada. This will be done utilizing the sea surface temperature (SST) in both the GOM and the Scotian Shelf as well as the bottom temperature in the GOM. There are four main research questions for this study. The first question is: Are there any patterns between SST and Northern Shrimp biological variables in either the GOM or the Scotian Shelf? The second question is: Are there any patterns between bottom temperature and Northern Shrimp biological variables in the GOM? The third question is: Is this relationship occurring in any other locations? Finally, the last question is: What are the potential drivers behind the relationship between water temperature and Northern Shrimp populations and what is the evidence for those relationships?

Methods

This study took place over both the Gulf of Maine and Eastern Canada. The GOM has experienced severe declines in Northern Shrimp populations since 2014 and more information was desired to determine possible reasons for the decline. The GOM is characterized by its complex geomorphology and semi-enclosed sea environment (U.S. National Park Service, 2021). It is a very active ecosystem with many different organisms occupying its seafloor and waters. The GOM spans from Nova Scotia down to Cape Cod, Massachusetts (U.S. National Park Service, 2021). Georges Bank and the Bay of Fundy surround the GOM as well as the Atlantic Ocean (U.S. National Park Service, 2021). It has a very complex ocean floor ranging from shallow banks to very deep basins (U.S. National Park Service, 2021). This allows for many different organisms to occupy the waters including benthic species such as Atlantic Halibut to pelagic species such as Bluefin Tuna (U.S. National Park Service, 2021). It spans over 36,000 square miles until reaching the edge of the continental shelf (U.S. National Park Service, 2021). It is also the location of around 60 freshwater river deltas further making it a unique aquatic ecosystem (U.S. National Park Service, 2021). Furthermore, ocean circulation frequently results in warm water from the Gulf Stream being brought up and deposited in the GOM (U.S. National Park Service, 2021). Ocean circulation combined with tidal mixing results in large fluctuations and changes in water temperatures in the GOM (U.S. National Park Service, 2021). These fluctuations have resulted in increases in the overall water temperature in the GOM. Georges Bank is closer to the surface of the ocean than the GOM so it acts as a barrier to the deeper water being able to move in and out of the GOM (Mills et al., 2023). The result has been an ongoing increase in Sea Surface Temperature (SST). 2021 and 2022 were noted to be the two warmest years on record for the GOM rising more than 3ºF over the long-term average (Mills et al., 2023). Overall, the GOM’s complex geomorphology and temperature phenomena as well as its decreasing Northern Shrimp population made it a very interesting study area.

Eastern Canada was also investigated for its Northern shrimp populations and fisheries. However, Eastern Canada encompasses many different locations, populations, and fisheries, so for the simplicity of the study, the Eastern Scotian Shelf was focused on due to its proximity to the GOM and the possibility of what is occurring in the GOM also occurring along the Scotian Shelf. The Eastern Scotian Shelf is located along the Southeast edge of

Nova Scotia, just Northeast of the GOM (Breeze et al., 2018). It, much like the GOM, is along the continental shelf before reaching the Atlantic Ocean (Breeze et al., 2018). The Scotian Shelf is 46,000 square miles featuring many shallow banks and a few deep basins (Breeze et al., 2018). Very little tidal mixing is present along the Scotian Shelf as it is not surrounded by land like the GOM, however, it is still home to many unique organisms (Breeze et al., 2018). Cod populations plummeted in 1993 leaving room for shellfish populations to grow and they have now become the main commercial species (Breeze et al., 2018). A flow of subpolar water impacts the temperature of the Scotian Shelf as it moves towards the equator (Breeze et al., 2018). This cool water comes from the North through the Labrador and Newfoundland shelf, past the Gulf of St. Lawrence, and to the Scotian Shelf (Breeze et al., 2018). The Gulf Stream has very little effect on the water temperature as it circulates right before reaching the Scotian Shelf. Despite the small effects of the Gulf Stream, the Scotian Shelf is experiencing overall increases in water temperature (Breeze et al., 2018). This resulted in the Scotian Shelf being chosen to be a study area because it appears to be at risk of Northern Shrimp population decline in the future.

A majority of the data utilized for this study is from stock assessments on the Northern Shrimp population that were conducted by the National Oceanic and Atmospheric Association (NOAA) or by Fisheries and Ocean Science Canada. Stock Status, Management, Assessments, and Resource Trends (SMART) by NOAA was also commonly used to determine the history and management of both Northern Shrimp and their predators. To find Northern shrimp data for other locations, the fishery stock status assessment was utilized to find the landings over time. As for Eastern Canada, the landings data found from 1982 to 2014 was from the Eastern Scotian Shelf Shrimp Framework 2015 which was published by Fisheries and Oceans Canada. The landings data for 2016 through 2021 was from the yearly stock status update of Eastern Scotian Shelf Northern Shrimp that was also conducted by Fisheries and Oceans Canada. Next, the SSB and total biomass data from 2011 to 2021 were also found from the yearly stock status update of Eastern Scotian Shelf Northern Shrimp conducted by Fisheries and Oceans Canada. The Scotian Shelf SST was extracted from a graph from a paper about the oceanographic conditions on the Scotian Shelf during 2022 that was published by Fisheries and Oceans Canada. From these graphs, an SST was estimated for each year and put into a spreadsheet to be used for analysis. As for the GOM, recruitment, SSB, and total biomass were found from the Northern Shrimp Stock Assessment update from 2021. This was prepared by the Atlantic States Marine Fisheries Commission, and conducted by NOAA. The SST for the GOM was found from the NOAA Optimum Interpolation SST (OISST) Version 2.1. and posted by the University of Maine. This data is collected using a mix of buoy, satellite, and ship observations and then converted to a usable dataset which I utilized for my research. Finally, the GOM bottom temperature was found from a graph in a University of Maine thesis paper that examines the changes in the GOM Northern Shrimp fishery. I utilized this graph to extract data about the bottom temperatures for each year I then moved to a spreadsheet to analyze.

Data Analysis

The GOM Sea Surface Temperature

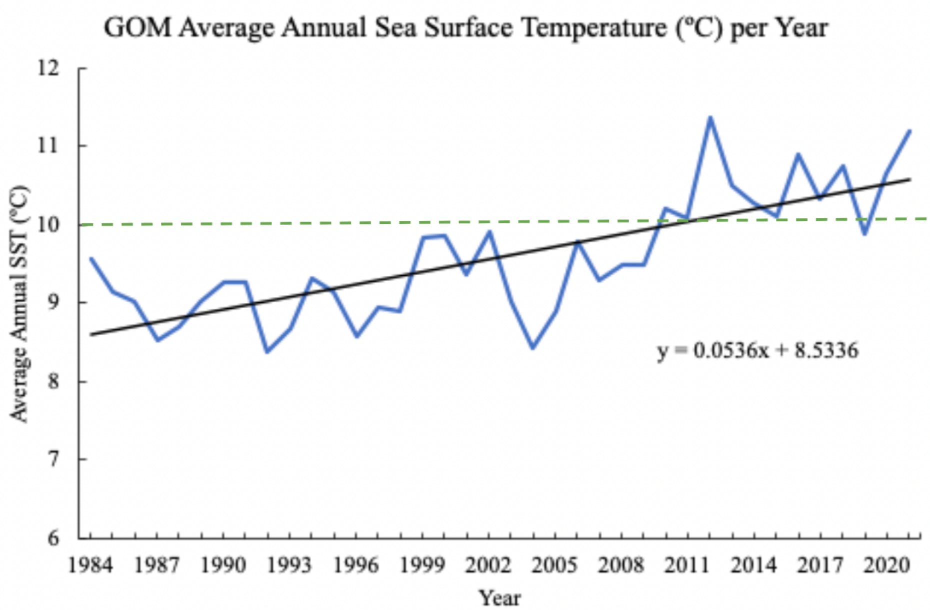

Figure 1. Sea Surface Temperature (SST) in degrees Celsius on the y-axis over time in years on the x-axis. The SST is shown from 1984 to 2021 increasing an average of 0.05ºC per year. 2011 was the first year that SST surpassed 10ºC. A green dashed line was included at the 10ºC SST point. Annual average SST was found by adding up the average SST for each day of the year and dividing it by 365 or 366 days (depending on if it was a leap year or not).

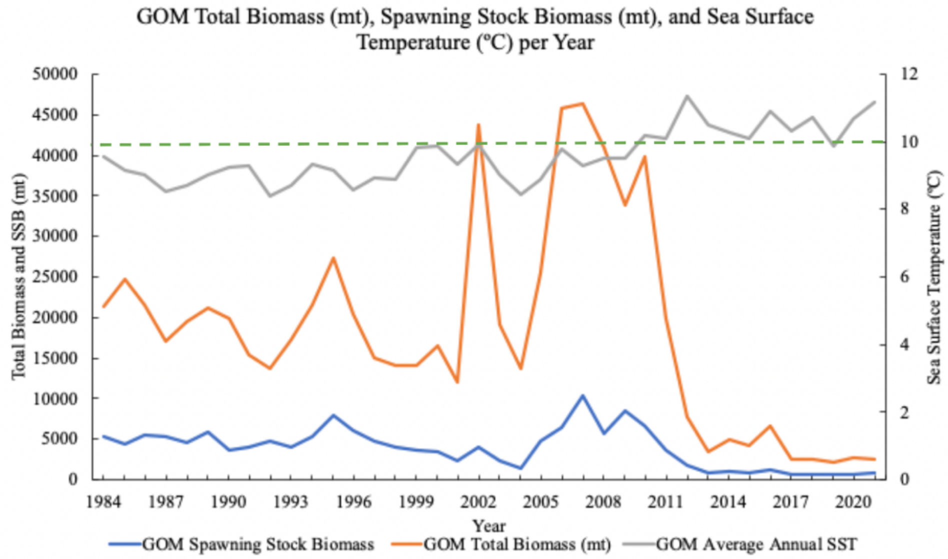

Figure 2. The total biomass (orange) and spawning stock biomass (SSB) (blue) is on the primary y-axis in metric tonnes. These two biological variables are compared to the average annual sea surface temperature (SST) (gray) from 1984 to 2021 on the x-axis. A green dashed line was included at the 10ºC SST point. Total biomass is found by multiplying the survival rate in an area by the average shrimp body weight by a specific time period (e.g. one year). SSB was calculated through the combined weight of all individuals that have reached sexual maturity and are able to reproduce. Annual average SST was found by adding up the average SST for each day of the year and dividing it by 365 or 366 days (depending on if it was a leap year or not). SST surpassed 10ºC for the first time in 2011. Total biomass fell from 39,774.6 mt in 2010 to 3,534.8 mt in 2013 which is a 90% decline. SSB declined from 8,427.9 mt in 2009 to 1,794 mt in 2012 which is an 85% decrease.

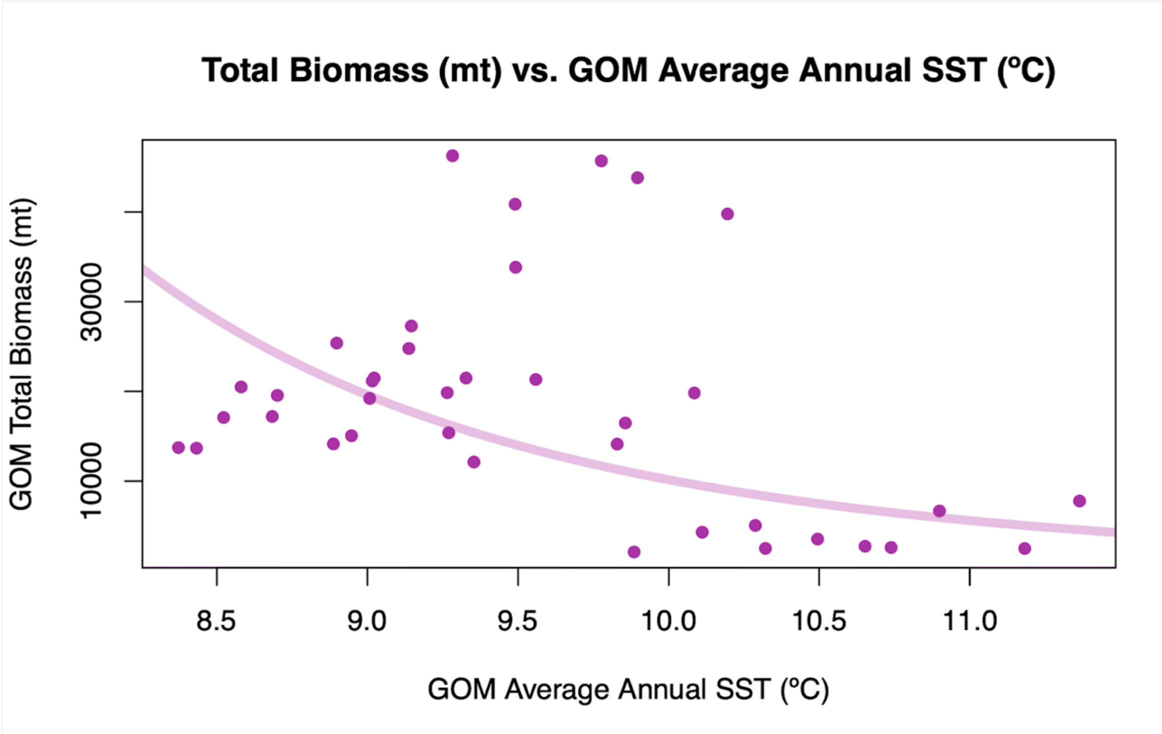

Figure 3. Total biomass is represented on the y-axis in metric Tonnes and was compared to the GOM average annual SST on the x-axis in degrees Celsius using a log-linear regression model. Both SST and total biomass were log-transformed variables to try and address the skewed data and bring it closer together so that the data was equally distributed. A significant negative relationship was found between SST and total biomass (P- value = 0.0003, R^2 = 0.3132). Biomass declines with temperature but the effect of temperature on biomass appears to lessen as temperature increases.

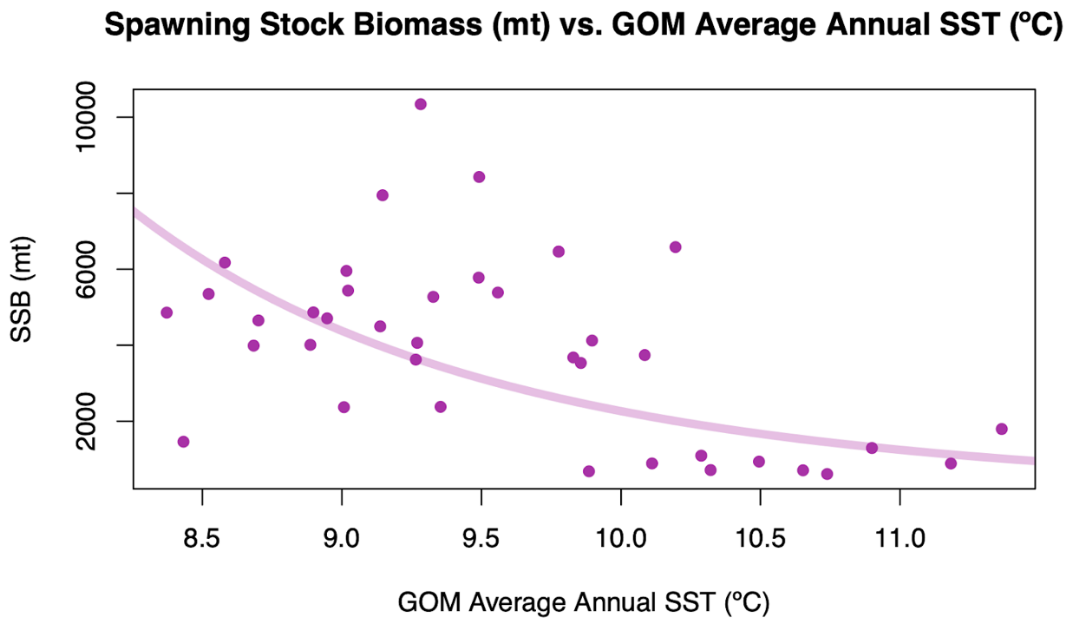

Figure 4. Spawning stock biomass (SSB) is represented on the y-axis in metric Tonnes and was compared to the GOM average annual SST on the x-axis in degrees Celsius using a log-linear regression model. Both SST and SSB were log-transformed variables to try and address the skewed data and bring it closer together so that the data was equally distributed. A significant negative relationship was found between SST and SSB (P- value = 3.87×10^{-5}, $R^2 = 0.3792$). SSB declines with temperature but the effect of temperature on biomass appears to lessen as temperature increases.

The GOM Bottom temperature

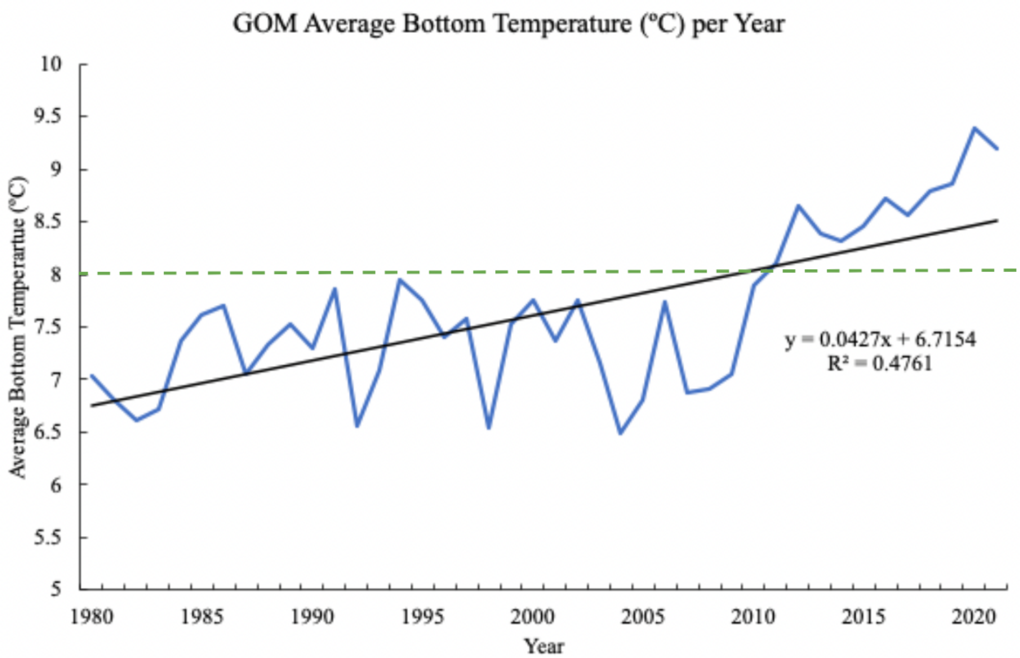

Figure 5. Bottom temperature in degrees Celsius on the y-axis over time in years on the x-axis. The bottom temperature is shown from 1980 to 2021 increasing an average of 0.043ºC per year. 2011 was the first year that bottom temperature surpassed 8ºC. A green dashed line was included at the 8ºC bottom temperature point. Annual average bottom temperature was found from previous literature and extracting the data from their figure (Charleson, 2020)

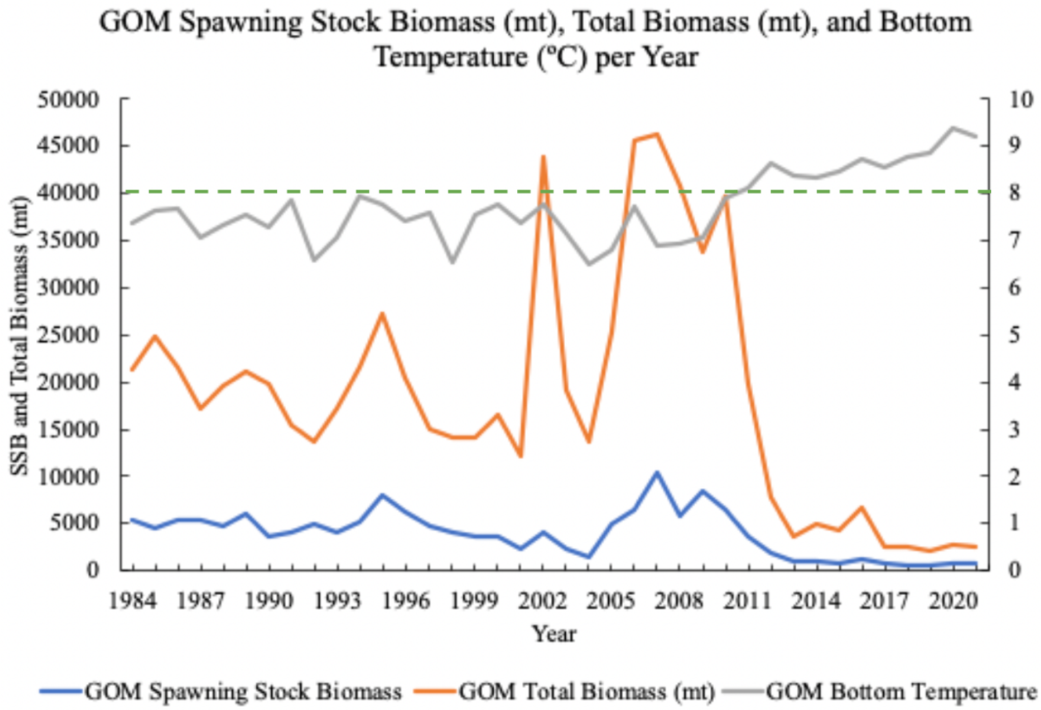

Figure 6. The total biomass (orange) and spawning stock biomass (SSB) (blue) is on the primary y-axis in metric tonnes. These two biological variables are compared to the average annual bottom temperature (gray) from 1984 to 2021 on the x-axis. A green dashed line was included at the 8ºC bottom temperature point. Total biomass is found by multiplying the survival rate in an area by the average shrimp body weight by a specific time period (e.g. one year). SSB was calculated through the combined weight of all individuals that have reached sexual maturity and are able to reproduce. Annual average bottom temperature was found from previous literature and extracting the data from their figure (Charleson, 2020). Bottom temperature surpassed 8ºC for the first time in 2011. Total biomass fell from 39,774.6 mt in 2010 to 3,534.8 mt in 2013 which is a 90% decline. SSB declined from 8,427.9 mt in 2009 to 1,794 mt in 2012 which is an 85% decrease.

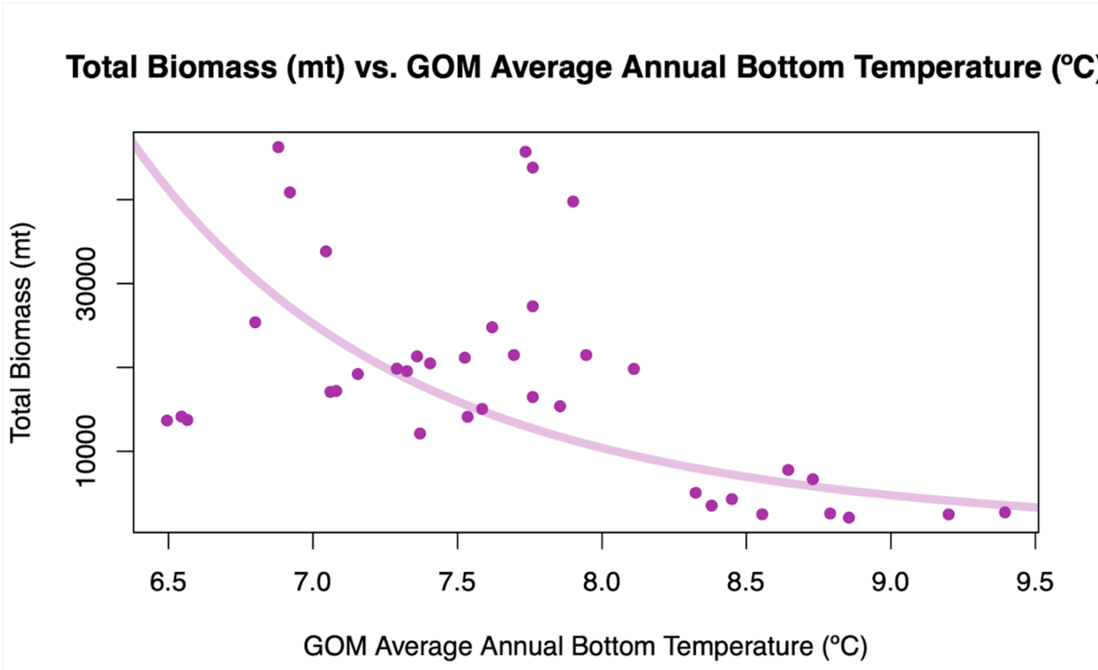

Figure 7. Total Biomass is represented on the y-axis in metric Tonnes and was compared to the GOM average annual bottom temperature on the x-axis in degrees Celsius using a log-linear regression model. Both bottom temperature and total biomass were log-transformed variables to try and address the skewed data and bring it closer together so that the data was equally distributed. A significant negative relationship was found between bottom temperature and total biomass (P- value = 9.41×10^{-7}, $R^2 = 0.4917$). Total biomass declines with temperature but the effect of temperature on biomass appears to lessen as temperature increases.

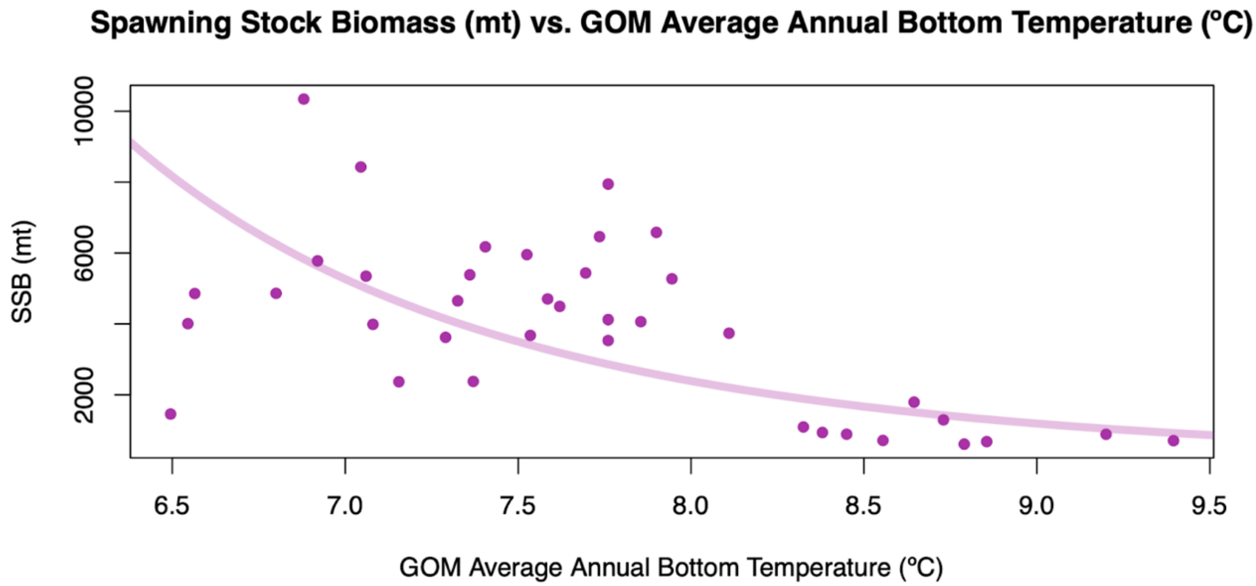

Figure 8. Spawning stock biomass (SSB) is represented on the y-axis in metric Tonnes and was compared to the GOM average annual bottom temperature on the x-axis in degrees Celsius using a log-linear regression model. Both bottom temperature and SSB were log-transformed variables to try and address the skewed data and bring it closer together so that the data was equally distributed. A significant negative relationship was found between bottom temperature and SSB (P- value = 1.89×10^{-6}, $R^2 = 0.4721$). SSB declines with temperature but the effect of temperature on biomass appears to lessen as temperature increases.

Eastern Canada and the Scotian Shelf

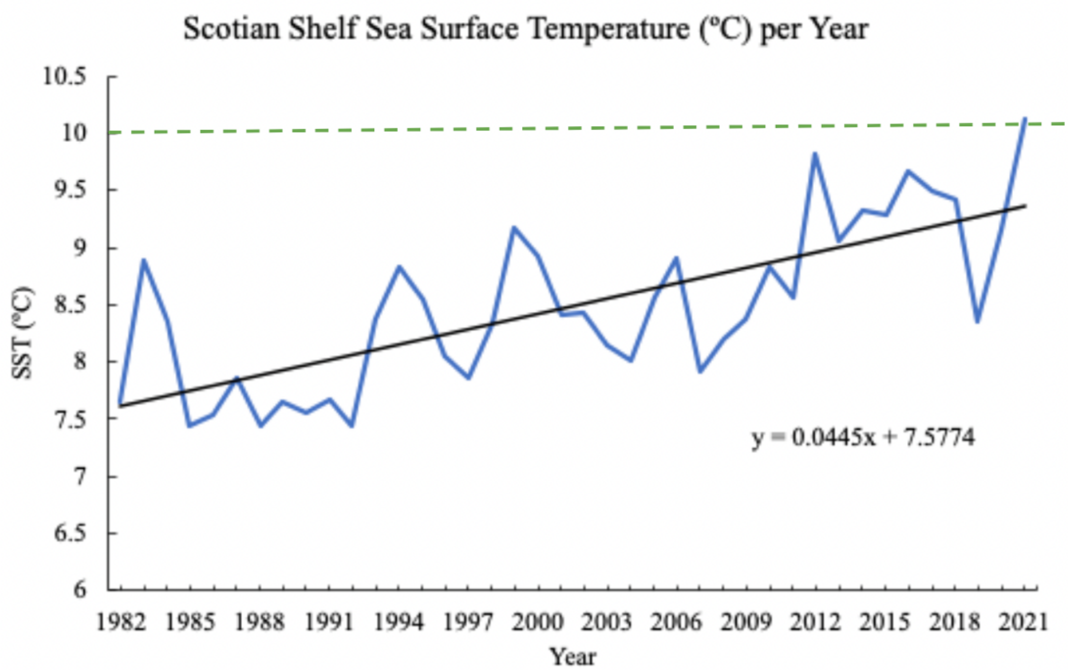

Figure 9. Sea Surface Temperature (SST) in degrees Celsius on the y-axis over time in years on the x-axis. The bottom temperature is shown from 1982 to 2021 increasing an average of 0.045ºC per year. A green dashed line was included at the 10ºC SST point. 2021 was the first year that bottom temperature surpassed 10ºC. Annual average SST was found from previous literature and extracting the data from their figure (Wang et al., 2024).

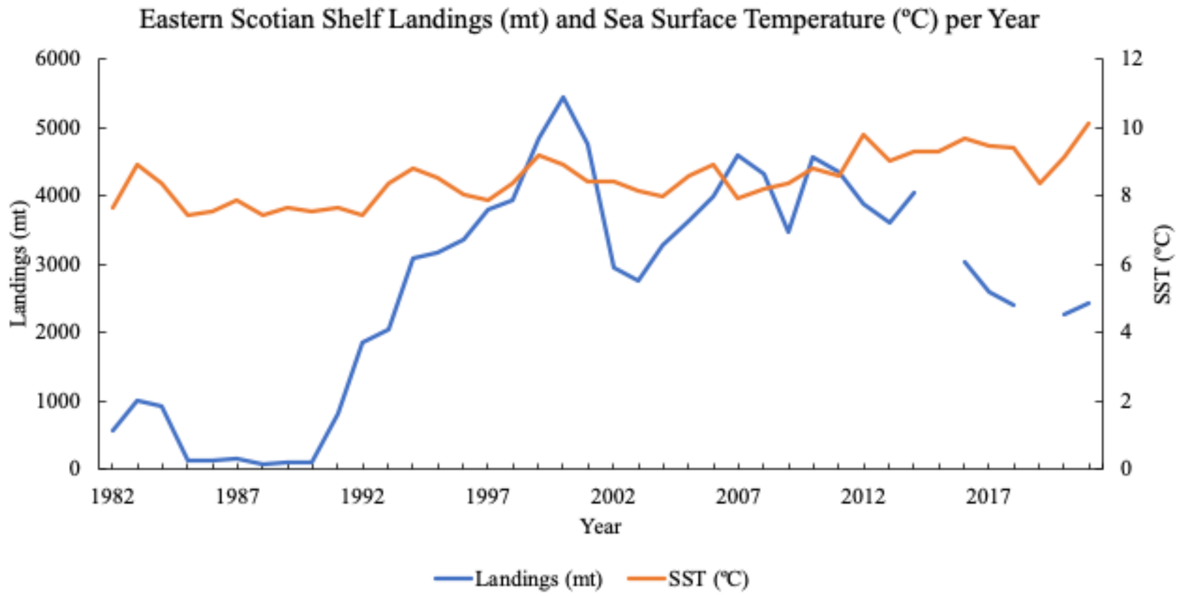

Figure 10. The landings (blue) is on the primary y-axis in metric tonnes. Landings were compared to the average annual sea surface temperature (SST) (orange) on the secondary y-axis over time from 1982 to 2021 on the x-axis. Landings were measured from the Scotian Shelf port that were reported by fishermen. Annual average SST was found from previous literature and extracting the data from their figure (Wang et al., 2024). SST surpasses 10ºC for the first time in 2021. Landings stay fairly consistent with no large drops in the past 20 years since the fishery started growing from 1990 to 1999.

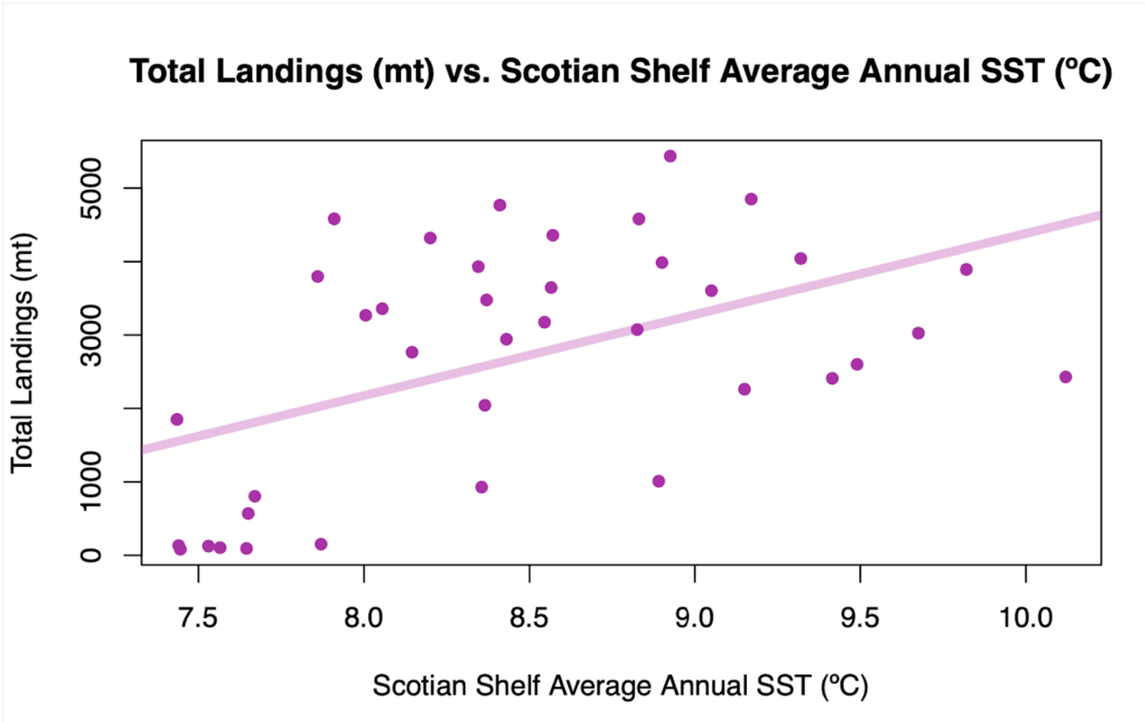

Figure 11. Total landings are represented on the y-axis in metric Tonnes and were compared to the average annual SST on the x-axis in degrees Celsius using a linear regression model. A significant positive relationship was found between SST and landings (P-value = 0.0015, R^2 = 0.2461). Total landings increase with temperature.

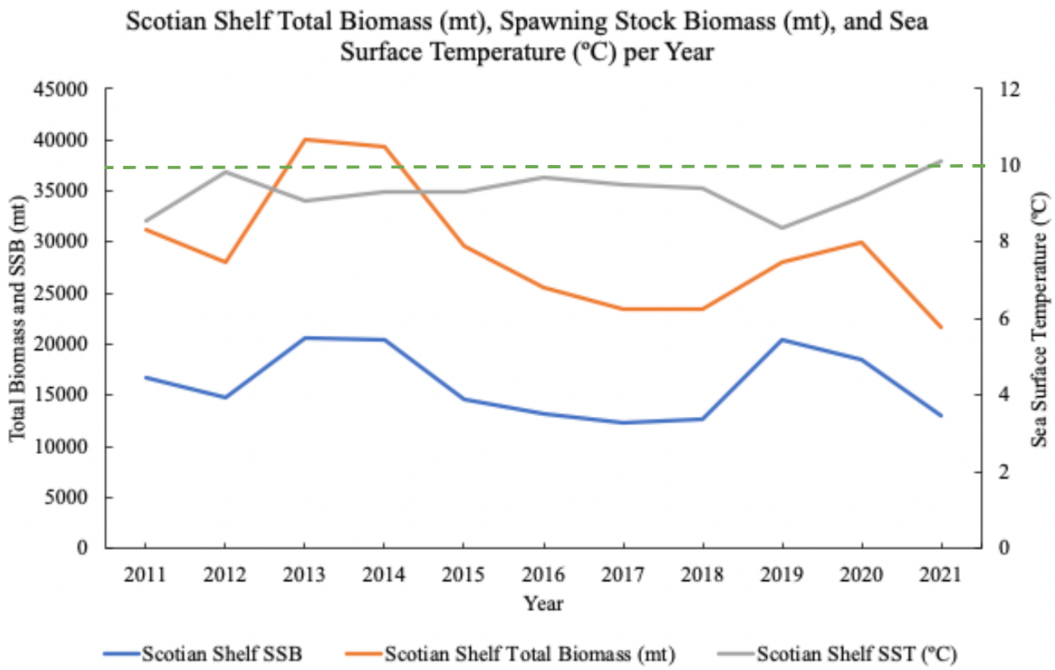

Figure 12. The total biomass (orange) and spawning stock biomass (SSB) (blue) is on the primary y-axis in metric tonnes. These two biological variables are compared to the average annual SST (gray) from 2011 to 2021 on the x-axis. A green dashed line was included at the 10ºC SST point. Total biomass is found by multiplying the survival rate in an area by the average shrimp body weight by a specific time period (e.g. one year). SSB was calculated through the combined weight of all individuals that have reached sexual maturity and are able to reproduce. Annual average SST was found from previous literature and extracting the data from their figure (Wang et al., 2024). SST surpasses 10ºC for the first time in 2021. Both total biomass and SSB stay fairly constant with slight fluctuations.

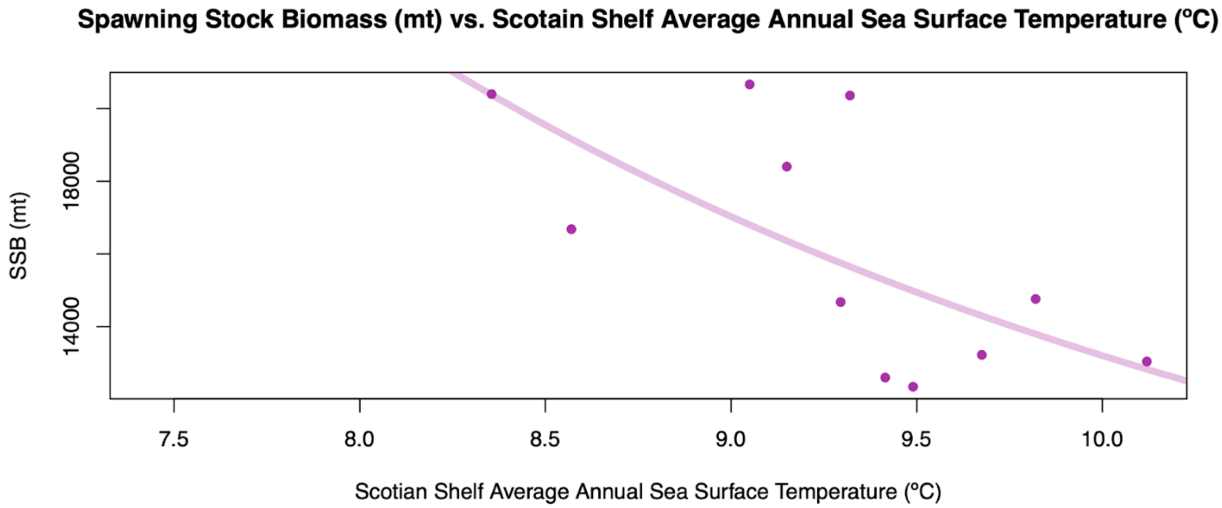

Figure 13. Spawning stock biomass (SSB) is represented on the y-axis in metric Tonnes and was compared to the Scotian Shelf average annual SST on the x-axis in degrees Celsius using a log-linear regression model. Both SST and SSB were log-transformed variables to try and address the skewed data and bring it closer together so that the data was equally distributed. A significant negative relationship was found between SST and SSB (P- value = 0.0268, R^2 = 0.4371). SSB declines with temperature but the effect of temperature on biomass appears to lessen as temperature increases.

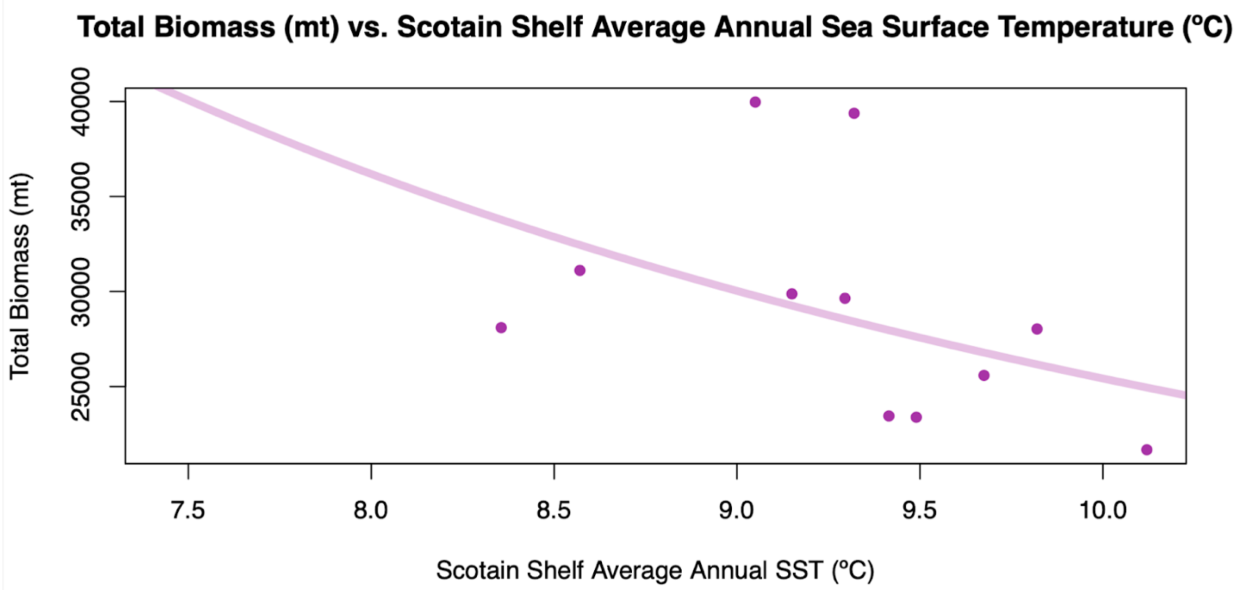

Figure 14. Total biomass is represented on the y-axis in metric Tonnes and was compared to the Scotian Shelf average annual SST on the x-axis in degrees Celsius using a linear regression model. An insignificant negative relationship was found between SST and total biomass (P-value = 0.1692, R^2 = 0.1989). Total biomass declines with temperature but the effect of temperature on biomass appears to slightly lessen as temperature increases.

Other locations

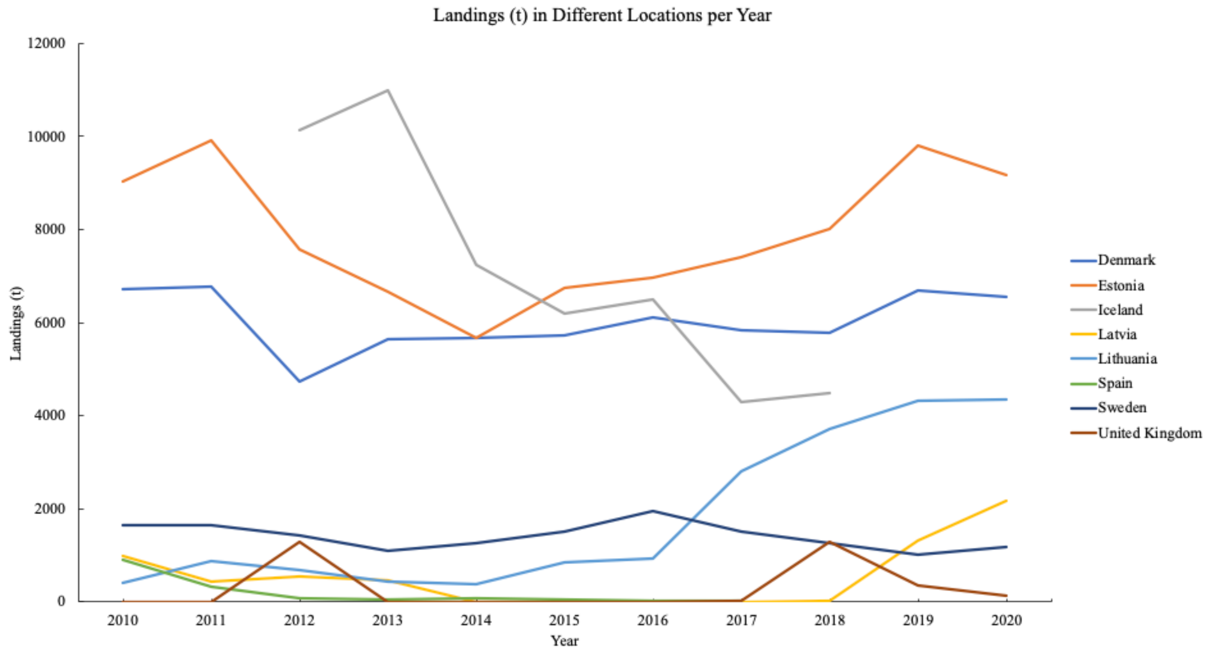

Figure 15. Landings are on the primary y-axis in metric tonnes over years from 2010 to 2020 on the x-axis. Landings were measured by country that were reported by fishermen. The different locations include Denmark (dark blue), Estonia (orange), Iceland (gray), Latvia (yellow), Lithuania (light blue), Spain (green), Sweden (purple), and the UK (burgundy).

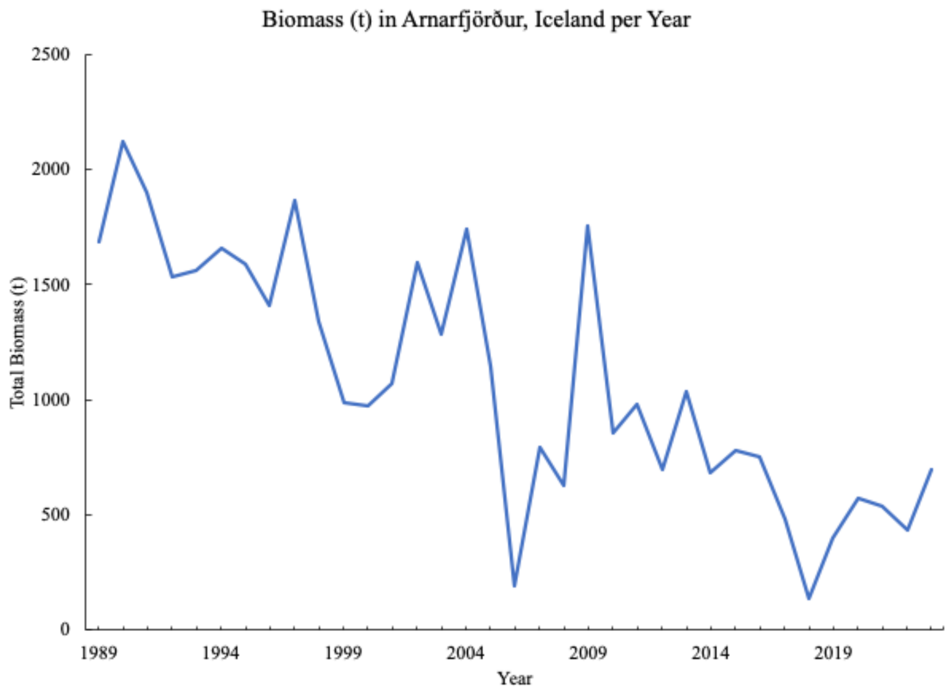

Figure 16. Total landings in Tonnes per year in Arnarfjörǒur, Iceland from 1989 to 2023. Biomass decreased from 1756 t in 2009 to 698 t in 2018.

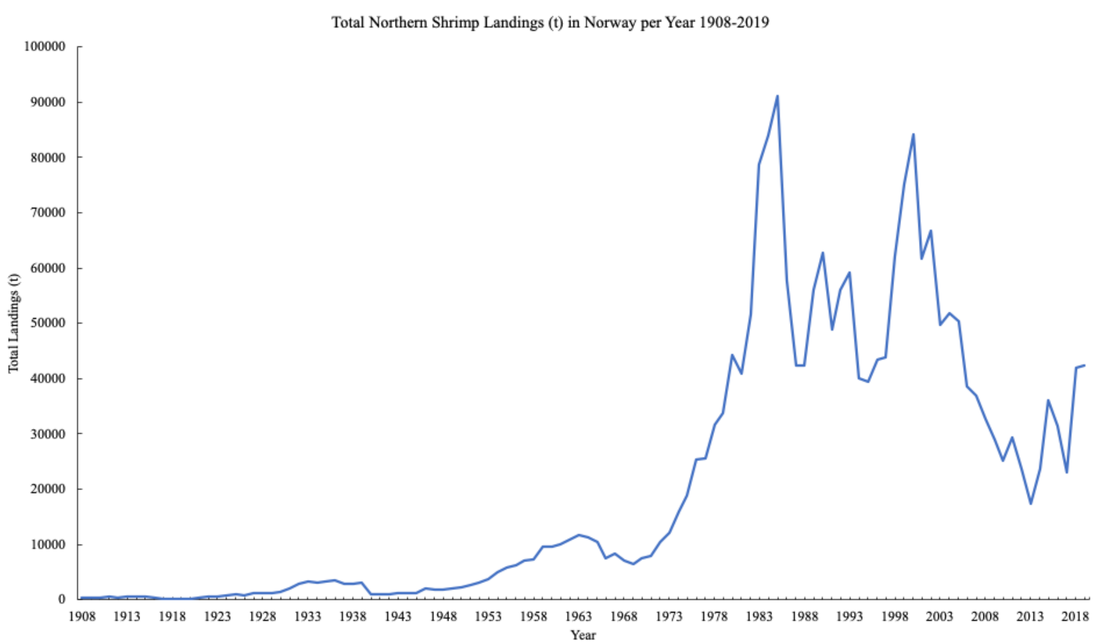

Figure 17. Total landings in Tonnes per year in Norway from 1908 to 2018. Landings decreased from above 80,000 t in 2000 to less than 20,000 t in 2013.

Results

Sea surface temperature (SST) was utilized to determine any possible trends and relationships between Northern Shrimp in the GOM and ocean water temperatures. Therefore a comparison between SST and Northern Shrimp biological data was conducted. The biological characteristics included biomass, spawning stock biomass (SSB), and recruitment. There is a positive trend in the average SST over time with a 0.5ºC increase from 2013 to 2023 and an average increase from 1984 to 2023 of 0.05ºC per year (Figure 1). There is also a decline in total biomass in years 2010 and 2011 dropping 90% from 39,774 mt and the populations have remained low since (Figure 2). SSB also demonstrated a large decline in SSB in 2010 and 2011 dropping 85% from 8,427mt (Figure 2). This relationship did not occur in the recruitment graph (Appendix Figure 1). A negative relationship was found between SST and total biomass with a significant P-value of 0.0003 and an R^2 value of 0.3132 (Figure 3). There is also the presence of a sharp decline in total biomass for any temperature over 10.1ºC (Figure 3). Any temperature below 10.1ºC the total biomass is at relatively healthy levels but above that the total biomass drops to unsustainable levels. There is a similar, significant relationship between SSB and SST with a P-value of 3.87×10^{-5} and an R^2 value of 0.3792 (Figure 4). The sharp decline also occurred in this graph around 10.1ºC where SSB levels were healthy below 10.1ºC but dropped close to 0 above 10.1ºC (Figure 4).

Bottom temperature, however, is more applicable to Northern Shrimp populations because they are a benthic species once they grow out of the juvenile stage and they tend to live on the ocean floor. Therefore, comparisons between bottom temperature and biological data could be more informative about any relationships. The overall bottom temperature in the GOM has a very positive trend very noticeably increasing 1.84ºC from 1984 to 2021 (Figure 5). The trendline demonstrates that every year the bottom temperature increases by 0.043ºC (Figure 5). This is about the same rate of increase as the SST. In 2011 bottom temperature surpassed 8ºC for the first time, which is the same time frame that total biomass fell from 39,774.6 mt in 2010 to 3,534.8 mt in 2013 which is a 90% decline (Figure 6). SSB also declined from 8,427.9 mt in 2009 to 1,794 mt in 2012 which is an 85% decrease (Figure 6).

Bottom temperature was compared to biological data about Northern Shrimp in the GOM. Bottom temperature demonstrated a significant negative relationship with total biomass with a P-value of 9.41×10^{-7} and R^2 value of 0.4917 (Figure 7). Similar to what was seen with SST, the population crash occurred in 2010 and 2011 which is when there was an increase in average bottom temperature, surpassing 8ºC for the first time (Figure 7). Total biomass drops when bottom temperature surpasses 8.1ºC dropping from healthy levels above 8.1ºC to close to 0 for any temperature above 8.1ºC. Bottom temperature was also compared to SSB and there was a significant negative relationship with a P-value of 1.89×10^{-6} and R^2 value of 0.4721 (Figure 8). Yet again, there was a sharp decline in SSB for any temperature above 8.1ºC from healthy levels below 8.1ºC. Recruitment did not demonstrate this same trend (Figure 8).

The impacts of warming ocean waters were also investigated in Eastern Canada, specifically off the coast of the Scotian Shelf. The goal was to determine if there was the same relationship between water temperature and biomass in Eastern Canada as there was in the GOM. The SST in Eastern Canada has a positive trend increasing 0.045ºC per year and rising 2.5ºC in the past 40 years (Figure 9). Although it is a different location, the GOM and Eastern Canada water temperatures are increasing at about the same rate. From 1982 to 2021 the total landings did not demonstrate a significant decline over time, staying fairly constant from 5,000 mt to 7,000 mt (Figure 10). However, it can be seen that total landings are in a downward trend from 2014 to 2021 (Figure 10). Eastern Canada SST and landings have a significant positive relationship with a P-value of 4.943×10^{-5} and a R^2 value of 0.371 (Figure 11). Although this demonstrates a significant relationship, the data never breaches 10ºC (except in 2021) which is the temperature that a noteworthy decline was observed in the GOM.

Further analysis was conducted to investigate relationships between Eastern Canada SST and biological data. This is important because landings can fluctuate from outside sources more than total biomass and SSB. If fishing effort decreases or fewer permits are given out, the landings are going to drop independently of the Northern shrimp stock health. Data, however, was limited so it is a short time frame only ranging from 2011 to 2021. However, this is an important time frame because it is when significant declines in Northern Shrimp biomass and SSB were observed in the GOM. The data was collected from the

Scotian Shelf in Eastern Canada because it is just Northeast of the GOM and was noted to have warmer water temperatures than further up North, making it likely to be the next place to feel the effects of warming water temperatures on Northern Shrimp populations. A drop in total biomass occurred from 2014 to 2021, decreasing from ~40,000 mt to ~22,000 mt (Figure 12). Although not as large of a drop as the GOM, it is still quite significant as the total biomass in 2021 was just over half the size of the total biomass in 2014. SST has a positive trend rising 0.045ºC per year with it almost reaching 10ºC in 2021. However, this impact from the increasing temperature was not noticeable in Northern Shrimp spawning stock biomass from 2011 to 2021 (Figure 12). The SSB appears to be fairly constant and healthy even with the warming temperatures.

Further analysis was done to determine if the relationships between SST and the biological variables seen in the GOM were also seen on the Scotian Shelf. A significant negative relationship between SSB and SST was found on the Scotian Shelf with a P-value of 0.023 and an R^2 value of 0.4371 (Figure 13). However, total biomass and SST did not have a significant relationship with a P-value of 0.1692 and R^2 value of 0.1989 (Figure 14). This insignificant relationship, however, could be attributed to the fact that there was only ten years worth of biological data on the Scotian Shelf that could be utilized. The relationship could also have been insignificant because it was below the 10ºC temperature threshold that was seen to have a large impact on total biomass in the GOM.

Other locations with Northern Shrimp fisheries were explored to determine if there were any sharp declines in their populations in any other place. Figure 15 is a graph that depicts eight different locations with Northern Shrimp fisheries and none show any obvious declines in Northern Shrimp population aside from Iceland. Therefore, a more in-depth analysis was done on the population of Northern Shrimp in Arnarfjörǒur, Iceland (Figure 16). An overall decreasing shrimp population trend was found in the data from 1990 until 2023 with a particularly sharp decline from 2009 to 2018 with the population dropping from 1756 mt to 698 mt (Figure 16). Norway was also investigated because it has a very large Northern Shrimp fishery. A graph was created of the total landings over time from 1908 to 2018 (Figure 17). There was a large crash in Northern Shrimp landings dropping from 2000 to 2013.

Discussion

The waters in the GOM are warming 0.045ºC a year as they begin to surpass the 10ºC barrier which evidence suggests could be the primary driver of population declines. The collapse in total biomass and spawning stock biomass (SSB) occurred the same year that 10ºC was passed in the average annual sea surface temperature in the GOM (Figure 2), and this isn't just a coincidence. It is further demonstrated through the log-linear regressions that there is a point when SST reaches over 10ºC that the SSB and total biomass drops to about 0 which demonstrates very little success for the Northern Shrimp population at any point over 10ºC (Figures 3 & 4). This same trend occurs in bottom temperature when it reaches over 8ºC. In 2011, the GOM bottom temperature first surpassed 8ºC and that corresponds with the sudden declines in both SSB and total biomass (Figures 6). Further scatter plots also show a huge decline in SSB and total biomass past 8ºC with both of them being close to 0 at any temperature above that barrier (Figures 7 & 8). It would appear that there is a correlation between the temperature both at the sea surface and bottom and these declines in SSB and total biomass. However, the populations of predators were also considered and none showed significant relationships to the years of decline for the Northern Shrimp populations but they could definitely be a factor (Appendix Figure 3).

In Eastern Canada, the waters are warming but at a slower rate than that of the GOM. This could be attributed to the lack of the Gulf Stream impacting water temperature and being cooled by the presence of the Labrador Current. However, there is still importance in investigating if the reduction of the Northern Shrimp population is still occurring on the Scotian Shelf, a neighboring section of the ocean. It is also useful to see if the same trends seen in the GOM are seen on the Scotian Shelf even though the water temperature there is lower than that of the GOM. Landings have remained fairly stable but have been showing a slight decline in recent years as the SST rises to reach the 10ºC tipping point of possible population collapse (Figure 10). The scatterplot of this relationship also demonstrates that there is currently no relationship between SST and landings at the current temperatures that are all still below the 10ºC where we saw the relationship in the GOM (Figure 11). Landings however are a difficult metric that are not very reliable because they are impacted by fishermen's efforts, gear, and other limitations that might not be related to temperature. Therefore, SSB and total biomass were also researched on the Scotian Shelf in regards to

SST. Both SSB and total biomass show a slight decline in metric tonnes from 2020 to 2021 as the SST rose to right around that 10ºC point (Figures 12). The water temperature, however, did not surpass that point so future years' temperature, SSB, and total biomass data could determine if this relationship exists in other locations. The log-linear regressions for the Scotian Shelf however both had negative trends in relation to increasing SST but they do not drop down to 0 like what is seen in the GOM (Figures 13 & 14). Looking further into other locations could also be important to determine if the Northern Shrimp population decline is an isolated incident for the GOM or if it is occurring in other locations as well. Nine locations with Northern Shrimp fisheries were explored and both Iceland and Norway demonstrated large declines in Northern Shrimp landings (Figures 15 & 17) and biomass (Figure 16).

The Gulf of Maine Sea Surface Temperature

The GOM temperature has risen just below 3ºC (2.992ºC) over the past 37 years with a low of 8.37ºC and a high of 11.36ºC. The overall trend of the GOM has been continuing to increase over these 37 years in the GOM at a rate of ~0.0536ºC per year (Figure 1). These warmer temperatures have resulted in large decreases in SSB and total biomass for the Northern Shrimp populations.

In 2011 a large collapse of the Northern Shrimp fishery occurred with total biomass crashing from 39,774.6 mt in 2010 to 19,827.9 mt in 2011 and continuing a downward trend to 3,534.8 mt in 2013 where it has continued to be since 2013 and the fishery moratorium being put into place in 2014 (Figure 2). This large collapse in the Northern Shrimp total biomass occurred the year following the first time the GOM average annual water temperature was over 10ºC (10.196ºC). A negative relationship between SST and total biomass was found when a log-linear regression was done (p-value of 0.0003). This can be seen by the large drop in total biomass right around the 10.2ºC mark where any year that was over 10.2ºC had close to 0 mt of biomass (Figure 3). This demonstrates that 10ºC is likely the tipping point from higher Northern Shrimp biomass and very low biomass.

A large collapse in SSB also occurred from 2009 to 2012 with 8,427.9 mt in 2009 and continuing on a downward trend to 1,794 mt in 2012 where it has not surpassed 1,500 mt since then (Figure 2). SSB is a large contributing factor to total biomass is found and it can be determined that a low SSB would likely contribute to the lower total biomass. This large collapse in SSB in 2009 combined with the increase in GOM SST in 2009 was preceding the collapse in total biomass that occurred in 2011. SSB also had a negative relationship with SST when a log-linear regression was done (p-value of 3.87×10^{-5}). The SSB data scatterplot shows that right around 10.1ºC there is a significant decline in SSB like what was also seen in the total biomass graph (Figure 4). Both of these results demonstrate the possibility of a temperature tipping point where Northern Shrimp SSB and total biomass both decrease to close to 0.

This change in SST likely had a large impact on the pelagic phase of the larvae released by the shrimp as they float around the water column close to the surface of the water. Richards et al. (2012) found that temperature had a large impact on the reproductive potential of the population and larvae. So the warmer waters had negative effects on the development and survival of the larvae floating near the surface of the water as well as making recruitment through reproduction lower (Richards et al., 2012). Although in this research no large impact was found in recruitment response to the increase in water temperature, it is possible that recruitment through immigration made up for the decrease in recruitment through reproduction and compensated for the overall decline. SSB and temperature directly factor into the recruitment of Northern Shrimp and could induce a decline in total recruitment if SSB is low (NOAA, 2024). A slight decline in recruitment did occur from 2010 to 2011 with recruitment declining from 18.4 to 3.1 billions of shrimp (Appendix Figure 1). So this decline in recruitment could be a consequence of the warming waters right around 10ºC and that could have led to the biomass collapse because reproduction recruitment directly impacts biomass as it impacts the starting life phase and can take out a whole class year of Northern Shrimp larvae (Richards et al., 2012). Arnberg et al. (2018) also determined that warmer SST causes life stage transition to take longer and require more energy. This results in a decrease in larval survival because larvae would spend more time in plankton feeding before settlement which makes them more vulnerable to predation (Arnberg et al., 2018). Arnberg et al. (2018) also found that the increased water SST reduces each individual's energy budget because it takes more energy to maintain homeostasis. This results in decreased growth and a higher risk of parasitism, infection, and death. Arnberg et al. (2018) also determined that the combination of warmer water temperatures (6.5ºC compared to 9.5ºC) and ocean acidification through changes in pH caused larvae survival to decrease by a factor of 1.3 and demonstrates that there is a huge threat for further population decline in response to fluctuations in pH and possible ocean acidification in the future. A study conducted by Chemel et al. (2020) considered the fact that the optimal temperature range for Northern Shrimp is -1.6ºC to 8.0ºC (Charleson, 2020) and found that there is a threshold for Northern Shrimp survival at 10ºC. Any temperature above the 10ºC thermal threshold results in severe thermal sensitivity within the Northern Shrimp population (Chemel et al., 2020). These papers as well as the results from this study demonstrate that as the SST breaches the 10ºC tipping point, the SSB declines almost to 0 in response to a lower larvae survival rate that is then reflected in other life stages. This lower SSB causes recruitment to decrease as well. The lowered SSB and recruitment along with warmer water temperatures results in total biomass decreasing to close to 0 as well.

The Gulf of Maine Bottom Temperature

SST can provide some very important context about the larval life stage and Northern Shrimp population growth. However, Northern shrimp spend all of their life stages aside from larvae and reproduction on the ocean floor because they are demersal species that tend to live in the muddy basins of the GOM where they feed on plankton and small bottom-dwelling invertebrates. Therefore, it is important to consider bottom temperature in the analysis because that is where a majority of their life, feeding, and spawning occurs.

Bottom temperature has had a fairly steady increase over time rising from 7.36ºC in 1984 to 9.2ºC in 2021 with an overall low of 6.495ºC and an overall high of 9.395ºC. The average annual bottom temperature increases 0.043ºC per year (Figure 5). 2011 was the first time that 8ºC was surpassed which is one year after the 10ºC was surpassed for SST which is predicted to be the threshold temperature for Northern Shrimp survival. At the same time, the total biomass collapse is occurring from 2010 to 2011 (Figure 6). The collapse likely began as a result of warmer SST which disrupted class year survival and then was further perpetrated on the ocean bottom by higher bottom temperatures. These warmer bottom temperatures could've caused earlier sex transitions which decreased female shrimp size, fecundity, and quantity of eggs produced. These warmer bottom temperatures could've also affected the prey distribution of the small invertebrates and plankton. A negative relationship was found between bottom temperature and total biomass when a log-linear regression was conducted (P-value = 9.41×10^{-7}). This can be seen by the fact that in the scatterplot once the bottom temperature surpasses ~8.1ºC the total biomass drops to nearly zero for any temperature over that threshold (Figure 7). This signifies that Northern Shrimp will not be able to survive in temperatures over that threshold.

This same trend can be observed in SSB with its response to the increasing bottom temperature. As mentioned before, SSB is a large contributing factor for total biomass so a sharp decline like what is seen in the Northern Shrimp population can have significant effects on the total biomass. The SSB decline began in 2009 but then really dropped between 2010 and 2012. This, much like total biomass, was likely a result of the SST being warm and then the bottom temperature following and warming as well. The same threshold of ~8.1ºC was found for SSB as a log-linear regression analysis was run between bottom temperature and SSB. A negative relationship was found between SSB and bottom temperature (P-value = 1.892×10^{-6}). This can be seen by the sharp decline in SSB for any temperature past ~8.1ºC (Figure 8). Therefore, SSB will be close to zero for any temperature over 8.1ºC meaning that very little spawning will occur past that threshold which has huge detrimental effects on the Northern Shrimp population, especially because spawning occurs within the deep muddy basins on the ocean floor so bottom temperature is extremely important.

The largest impacts of bottom temperature would likely be felt in size-at-sex-transition, spawning capabilities, and prey populations. These are all important because spawning, sex transition, and feeding all occur at the ocean floor and changes in bottom temperature likely have profound effects on the Northern shrimp population's survival. A study by Apollonio et al. (1986) investigated the impacts of water temperature on size-at-sex-transition as well as spawning capabilities. Apollonio et al. (1986) found that cooler water temperatures allow for delayed sex transition and maturity which permits a longer generation length. Therefore, if the water is warmer, maturity will occur at a quicker rate and sex-transition will occur earlier which results in a shorter generation length (they die younger). This study by Apollonio et al. (1986) is further supported by research done by Daoud et al. (2010) where they found that the intermolt period (IP) is shortened as temperature increases. This means that they move through life stages quicker and they die at a younger age in the elevated temperatures (Daoud et al., 2010). Apollonio et al. (1986) also determined that there is an inverse relationship between time of spawning and bottom temperature. Once shrimp are exposed to an environment with a bottom temperature higher than 8ºC they begin spawning earlier and there is a phenological mismatch between males and females because the females begin spawning and move inshore before the eggs have been fertilized by the males (Apollonio et al., 1986). This results in very little reproductive success when water bottom temperatures are over 8ºC which heavily supports the results from this study. This warm bottom temperature threshold is not as apparent in prey populations, but Lewandowska et al. (2014) found that there is a negative relationship between plankton biomass and water temperature. Therefore, as bottom temperature increases, plankton biomass decreases as well. This could be the result of top-down effects from the consumer being stronger because of more stress on the population due to the warmer temperatures. This is also important with SST because the larvae feed on plankton near the sea surface while they are in their pelagic stage. Burns (2018) also found that in places with sea ice plankton populations decline as sea ice decreases. This is important because sea ice is a big contributor to keeping the waters cool and as there is less sea ice the waters become warmer. The impacts of warmer bottom temperatures can be seen directly impacting size-at-sex-transition and lifespan as well as spawning capabilities and phenological mismatches. As for prey distribution, water temperature is important both at the bottom and on the surface because Northern Shrimp prey on plankton during all stages of life, and the warming water temperatures are causing their populations to decline which removes a necessary factor in the Northern Shrimp population's survival. The bottom temperature must stay below the 8ºC threshold in order to ensure that spawning can continue to occur and that the Northern Shrimp lifespan doesn't continue to shorten and make the population further shrink.

Eastern Canada and the Scotian Shelf

The effects of warming water temperatures in the GOM are profound with two thresholds being determined for Northern Shrimp population survival and success. Those two thresholds were ~10.1ºC for SST and ~8.1ºC for bottom temperature. There are impacts on Northern Shrimp success from surpassing these thresholds, but another location that could be affected by these warmer temperatures could be essential to determine if this is an isolated incident or could be a preview of what's to come for other Northern Shrimp stocks if global ocean warming isn't mitigated or stopped. Therefore, Eastern Canada can provide some very useful information and context to determine if the same trends and thresholds seen in the GOM are also occurring in Eastern Canada. To help narrow down the research zone, only the Eastern Scotian Shelf was researched because it is right next to the GOM, just a little farther North.

The waters on the Scotian Shelf have not risen as high as what is seen in the GOM, however they have still changed a lot. The SST in 1982 was 7.65ºC and the SST in 2021 was 10.12ºC which is a 2.47ºC change over 39 years. This means that there is an increasing SST trend of 0.045ºC per year (Figure 9). The lowest temperature was 7.44ºC and the highest was 10.12ºC which occurred in 2021 and was the first time the average annual SST was over 10ºC which was determined to be the threshold for Northern Shrimp success in the GOM. However, it is important to note that the Scotian Shelf is not as impacted by the Gulf Stream as the GOM is. The GOM is a mix of the currents from the Gulf Stream (warm waters) and the Labrador Current (cold waters). The Scotian Shelf only receives cool waters from the Labrador Current because the Gulf Stream circulates before it reaches the Scotian Shelf. This could explain why the temperature has been on average colder on the Scotian Shelf than in the GOM.

The Eastern Canada fishery landings, however, have not shown a large decline. There is definitely a decrease in landings but it is not as dramatic of a change as what was seen in the GOM. Landings dropped from 4,041 mt in 2014 to 2,429 mt in 2021 which was the first time the SST surpassed 10ºC (Figure 10). However, landings are not just impacted by Northern Shrimp population success, they are also impacted by management policy and fishing efforts. If the fishing effort decreases, it is logical that the landings would decrease as well. Therefore, a log-linear regression analysis was conducted to determine if there is a relationship between SST and landings. The regression found a significant p-value of 4.943×10^{-5} for a positive relationship between landings and SST (Figure 11). What is important to note about this relationship though is the ~10.1ºC threshold where population collapses in the GOM is not passed here. It is logical that we wouldn't see a significant negative correlation between the two variables when landings are so unreliable and dependent on other factors and the threshold point is not surpassed.

Due to the possibility of outside factors other than shrimp population impacting landings, total biomass and SSB were investigated to see if there is a trend between Scotian Shelf SST and those two biological variables. Both SSB and total biomass did not show any extremely sudden and significant declines from 2011 to 2021. The SSB remained fairly stable between 2011 and 2021 with slight fluctuations ranging from 12,347 mt in 2017 and 20,398 mt in 2019 (Figure 12). There is no obvious decline or drop-off in the data. However, it is notable that there is a cyclical inverse relationship between SST and SSB. It also appears that SSB is highly responsive to any small and slight changes in SST even below the ~10.1ºC threshold. A significant negative relationship was found between SST and SSB from the log-linear regression (P-value = 0.02675) (Figure 13). This significant negative relationship confirms that there is a relationship between SSB and SST even below the ~10.1ºC threshold but that it is not as significant as when there is data that is above this threshold.

The Scotian Shelf was also examined in regards to SST to see if the relationship seen between SST and total biomass in the GOM existed on the Scotian Shelf as well. Total biomass demonstrated a slight decline of 39,971 mt in 2013 to 21,670 mt in 2021 (Figure 12). This is still a fairly large decline but it is spread out over a larger quantity of years than what is seen in the GOM. An insignificant relationship between SST and total biomass was found in the log-linear regression analysis (P-value = 0.1692) (Figure 14). This could be attributed to the lack of data points because only ten years of biomass data was available to be included. The insignificant relationship could also be due to the fact that the ~10.1ºC threshold was not surpassed so the significant relationship seen in the GOM was not able to be seen in this data because all of the temperatures were less than ~10.1ºC.

These results between temperature and SST on the Scotian Shelf begin the conversation about whether Eastern Canada and the Scotian Shelf in particular could be the next location that is impacted by decreased Northern Shrimp populations in response to warming water temperatures. Koeller, (2000) determined that migrations in Northern Shrimp off the coast of the Scotian shelf are likely going to change in response to the warming waters. They want to live in a more suitable environment with cooler temperatures so the population will likely move north (Koeller, 2000). This can have large negative effects on the commercial Northern Shrimp Fishery as no more shrimp will be available to fish thus causing declines in landings like what is seen in Figure 14. The findings by Koeller (2000) are important because as the temperature rises not only will the survival of Northern Shrimp decrease as SST surpasses the threshold temperature, but the population will also be migrating out of the area. Furthermore, an experiment conducted by Brennan et al. (2016) investigated the response of Scotian Shelf Northern Shrimp to increased water temperatures of 9.5ºC which is just below the temperature threshold found to be present in the GOM. Brennan et al. (2016) found that an increased development rate was found at the elevated temperature which is the same result as what was found in the GOM. Brennan et al. (2016) determined that Northern Shrimp prefer cooler temperatures within the range of -1ºC to 8ºC which supports the findings for the Scotian shelf SST relationships because Northern shrimp thrive in up to 8ºC but they can still survive in 9ºC water and declines first begin when the temperature gets over 9.5ºC and the SST on the Scotian Shelf has remained around that temperature. However, if the SST continues to rise across the Scotian Shelf, it can be anticipated that the Northern Shrimp population will decline like what was seen in the GOM because it is too far outside of their normal range. In order to address the issue of how to manage the Northern Shrimp stock while these temperatures continue to rise, a new management plan needs to be created. A management plan that involves incorporating not only the data from the stock status (biomass, recruitment, SSB), but also water temperature into the datapoints being considered for setting catch limits and fishing permits. An inclusion of water temperature into those decisions could allow for a more proactive response to the population decline. If water temperature is rising towards the 10.1ºC threshold, the total allowable catch and number of permits should decrease in response. Therefore, a management plan that incorporates water temperature could be the most effective strategy for avoiding the initial drop in population size due to fishing pressure.

Other locations

In order to further determine if the decline that was seen in the GOM Northern shrimp stock was occurring anywhere else, all countries with Northern Shrimp fisheries were examined. These countries included Denmark, Estonia, Iceland, Latvia, Lithuania, Spain, Sweden, the United Kingdom (Figure 15), and Norway (Figure 17). Many of these countries had fairly steady populations with no significant growth or decline. However, both Iceland and Norway exhibited huge declines in their populations. Arnarfjörður, Iceland exhibited a decline in total biomass from 2,121 mt in 1990 to 432 mt in 2022 (Figure 16). The landings in Norway also had a large decline over the past few decades decreasing from 84,097.03 mt in 2000 to 42,311.9 mt in 2019 (Figure 17). In both of these locations, Northern Shrimp populations decreased by at least 50% over the course of a few decades. This could suggest that the possible SST and bottom temperature threshold has been reached or is getting close in both of these locations. In Arnarfjörður, Iceland, there was a cold spell in the 1960s and since then the waters have been continually warming (Astthorsson et al., 2007). Astthorsson et al. (2007) also determined that the plankton population has been low in the North in response to the warming water temperatures. The lack of phytoplankton means that a vital source of prey for the Northern Shrimp is gone so the shrimp could have died from lack of prey or changed their migration or distribution to be more closely aligned with the phytoplankton. In Norway, Stenevik and Sundby (2007) also determined that the Barents and North Sea are both warming at an alarming rate. This is likely to have negative impacts on marine organism distribution as cold water species move north and warmer water species move into the area (Stenevik & Sundby, 2007). Therefore, it is reasonable to infer that the Northern Shrimp are moving out of this fishery and going North to colder waters that are within their survival range. It is also likely that new predators are moving into this area of Norway as their distribution increases and they could be preying on the Northern Shrimp further causing their numbers to decrease. Overall, Norway and Arnarfjörður, Iceland serve as important evidence that this phenomenon of decreasing Northern Shrimp populations is occurring elsewhere due to emigration, and changes in prey and predators, much like what is being seen in the GOM.

Northern Shrimp populations are declining not only in the GOM but also in places like Iceland and Norway. This decline can heavily be attributed to the warming ocean temperatures and can serve as meaningful examples and warnings for other locations about the consequences of global ocean warming and its impact on cold-water aquatic species and ecosystems. Although Eastern Canada has not shown as distinct of a decline as what has been seen in the GOM, the warming waters on its coast are likely going to continue, driving the Northern Shrimp population to local extinction.

A threshold temperature was found where the Northern Shrimp total biomass and SSB both show a sharp decline. This threshold is 10ºC for SST and 8ºC for bottom temperature. Any temperature above those two thresholds demonstrated very little success and those temperatures demonstrate a tipping point for Northern Shrimp survival and success. Eastern Canada, more specifically the Scotian Shelf, is just now beginning to reach those threshold temperatures and it is extremely likely that those stocks will begin to decline soon if rapid action is not taken to reverse the warming. The beginning effects of the warming can already be seen on the Scotian Shelf because Koeller (2000) already determined that the Northern Shrimp are already migrating out of the Scotian Shelf and farther North where waters are cooler. They could also migrate in response to other factors found in Norway and Iceland of decreased prey populations (Astthorsson et al.,2007) or increased predator populations (Stenevik & Sundby, 2007). The Scotian Shelf could also begin experiencing the more direct effects of the warming waters like what is seen in the GOM. The huge drop-offs in SSB and total biomass occurred at ~10.1ºC for SST and ~8.1ºC for bottom temperature and the possible biological effects of the temperature increase include lower larvae survival and recruitment within the population as a result of the water temperatures making energy supplies lower and stress on the larvae higher so many individuals in the class don't survive (Richards et al., 2012; Arnberg et al., 2018). Chemel et al. (2020) found the SST threshold for thermal sensitivity and these biological effects begin at 10ºC which corresponds with the ~10.1ºC threshold found for this study. Bottom temperature is also an important characteristic as it is where sex transition, spawning, and a majority of their lifespan is spent. However, with elevated temperatures sex transition occurs earlier when the shrimp are smaller resulting in a lower fecundity and a shorter lifespan (Apollonio et al., 1986; Daoud et al., 2010). The warmer temperatures also can result in a phenological mismatch between females and males when they spawn and move inshore for egg release (Apollonio et al., 1986). All of these direct impacts felt in the GOM by the Northern Shrimp population occur at ~10.1ºC for SST and ~8.1ºC for bottom temperature. Although Eastern Canada is not quite at that temperature just yet, it is likely that as the ocean continues to warm it will surpass the 8.1ºC and 10.1ºC threshold and these direct biological effects will occur there as well. These impacts are not small and are a piece of why the Northern Shrimp population has been so far reduced in the GOM.

Another factor of climate change that was unable to be addressed through data analysis is the possibility of pH impacting Northern Shrimp survival. pH however, can be largely influenced by climate change and warming water temperatures. The pH content of the ocean also decreases as water temperature increases. The water becomes more acidic because the higher temperatures allow more Hydrogen ions to dissociate resulting in an overall lower pH (Frommel et al., 2011). The temperature anomalies that have been observed in the GOM have resulted in more frequent oscillations in pH content and the ability to form calcium carbonate which is the main component in Northern Shrimp shells (Salisbury & Jönsson, 2018). Therefore, the changes in pH could possibly have impacts on the Northern Shrimp shell formation which make them vulnerable to predation, parasites, and disease (Dupont et al., 2014). A study by Dupont et al. (2014) collected shrimp with a trawl from Sweden and put in tanks in a lab to determine the impacts of pH (8.0 and 7.5) on Northern Shrimp survival. In the more acidic tank of the predicted near-future ocean acidification (pH 7.5), mortality increased by 63% (Dupont et al., 2014). Furthermore, Guscelli et al. (2023) used a trawl to collect shrimp and hold them in tanks at a lab and also determined that shrimp survival decreased profoundly with increased pH, however water temperature was a bigger factor. This finding by Guscelli et al. (2023) agrees with Chemel et al (2020) who determined that a low pH in combination with increased water temperature severely decreased Northern Shirmp survival. However, pH doesn't change without the increase in water temperature, and the pH is not changing at the same alarming rate as what's seen in water temperature. Therefore, pH is a factor that can not be ignored as a possible contributor to Northern Shrimp population decline, however it does not currently appear to be as prevalent as the water temperature.

Although many of the results that were found in this study can be backed up by other research and literature, there were several limitations and caveats to what was found in these results. Those limitations and caveats include the outliers in the GOM total biomass versus SST graph, the outliers in the GOM total biomass versus bottom temperature graph, the lack of bottom temperature for the Scotian Shelf, the small dataset for Scotian Shelf biomass and SSB, the use of landings as a signifier for Northern Shrimp stock success, the outlier in GOM Northern Shrimp recruitment, and a lack of information on some Northern Shrimp stocks located in Russia and China.

The outliers present in the two log-linear regression models for total biomass versus SST or bottom temperature can be found right before the temperature threshold of 10.1ºC and

8.1ºC and they appear to spike way higher than the other datapoints. There is no clear reason as to why this pattern exists or what is causing these datapoints to differ from the otherwise noticeable trend, however some possible reasons could be changing predator dynamics, changing prey dynamics, or overall oscillations in the population dynamics before the crash. There could have been a large jump in plankton biomass between 9.4ºC and 10.1ºC because the warmer water allowed for the plankton to photosynthesize more which provided more food for the Northern Shrimp to feed on. However, once the water temperature got over 10.1ºC not only could the shrimp not survive, but neither could the plankton, so their populations decreased. Another possible mechanism for total biomass increase could be that there was reduced predator pressure within the temperature range of 9.4ºC and 10.1ºC. Atlantic Cod populations declined before Northern Shrimp when temperatures started rising, but it was before the temperature got high enough for Longfin Squid to be able to survive, so it is possible that within that time period between those two temperatures, there were less Northern Shrimp predators so their population could increase. Finally, the total biomass could have just increased due to oscillations in population dynamics right before a population crash. Other species such as the sockeye salmon experience population cycles that are dependent on recruitment and stock dynamics. With high recruitment years resulting in higher total biomass years and lower recruitment resulting in lower total biomass years. This same trend could have occurred in the Northern Shrimp population with high recruitment occurring right before the population crashed because recruitment decreased once the water temperature surpassed 10ºC for SST and 8ºC for bottom temperature. The reasons listed above, however are only speculations and not the only possible reasons for the outliers seen in the graph.

The second limitation of the lack of bottom temperature for the Scotian Shelf is important because it could've provided some helpful insight and information into the result that was found in the GOM. With the GOM being the only location with bottom temperature information it is difficult to analyze and compare the results to other locations which makes the results less reliable. There was only information on the Scotian Shelf SST and as mentioned before, marine heatwaves or temperature anomalies can occur independently of each other so there could be useful information if bottom temperature was known. Through that another limitation can be found in the Scotian Shelf data because there are only ten years of data for total biomass and SSB. By 2011 where the dataset for SSB and total biomass begins, the SST had already surpassed 8.5ºC and is mostly within the 9ºC zone. This lack of information eliminates the possibility of seeing if there was a large decline in SSB or total biomass because it's hard to see significant trends over such short periods of time. It also could be the reason as to why the regression for total biomass was not significant because it lacks enough data points to draw out a significant result. This problem was attempted to be solved by the use of landings compared to SST, but like what was mentioned earlier this is also a caveat because landings aren't exactly indicative of stock health. This is because landings can change based on things other than biomass such as fishing effort and management of the stock. For example, landings could go up or down based on the number of permits given out and utilized by fishermen. Therefore, it is unlikely that landings and stock health are exactly comparable which makes the results and findings slightly unreliable.

Another limitation of the study was the outlier in the GOM recruitment data in 2002. In 2002 recruitment jumped up to 45.7 billions of shrimp. The year before was 1.8 billion shrimp and the year after was 2.1 billion shrimp. The reasoning behind this huge jump in recruitment is unknown and caused any possible relationships between temperature and recruitment to be overshadowed when regression analysis was done. The recruitment in 2002 was over three times the recruitment in any other year in the whole data set from 1984 to 2021. When looking at the data without the 2002 outlier it appears that there is a drop-off between 2010 and 2011 but that information is not significant with the presence of the outlier. This makes the information less reliable for the findings of the study.

The final limitation of the study was the lack of information on the Northern Shrimp stocks and fisheries in China and Russia. The Northern Shrimp distribution includes the coast of Russia and China and fisheries for the populations do exist but very little information can be found about them, their landings, stock status, or water temperature. Therefore, they could not be included in the conversation about the stock status for other locations and it is unknown whether their populations are declining as a result of increased water temperature.

These limitations all either occurred because of a lack of data or insufficient data that make it more difficult to draw conclusions or make the conclusions slightly less reliable. Future studies could focus on trying to retrieve the data that was either insufficient or missing from this study and see if there are any further conclusions that can be found or verify the threshold temperatures for Northern Shrimp's success and survival.

The research and literature provided here gives some very important information and context for why we see the drop in the Northern Shrimp population in the GOM and if we can expect to see similar declines in other locations such as Eastern Canada. A ~10.1ºC threshold for SST and a ~8.1ºC threshold for bottom temperature are present in the GOM and demonstrate a lack of Northern Shrimp survival and success in SSB, recruitment, and total biomass after those thresholds are breached. Some of the direct impacts include shorter lifespan, phenological mismatch between male and female spawning, and smaller size-at-sex-transition which decreases fecundity. However, even before crossing that threshold, there are earlier indirect impacts that can be seen occurring in populations that haven't had a steep decline yet but have a slightly decreasing population over time while the water temperature increases. Some of these indirect effects include changes in prey and predator distribution. The location where Northern Shrimp is currently most impacted by the increasing water temperatures is the GOM. However, the drop in Northern Shrimp biomass in the GOM doesn’t mean that it can’t recover. In the 1950s there was a warm spell in SST resulting in a drop in Northern Shrimp biomass and landings dropping close to zero, but the population was able to recover and the fishery was able to continue functioning once the water temperature declined again (Dow, 1964). The SST seen in the GOM is the same as what was seen in the 1950s so finding a solution to cool the water again could be the answer to the problem. Further research needs to be done on how to mitigate the warming water temperatures and try to prevent further warming in the future so that the Northern Shrimp population can continue to survive.

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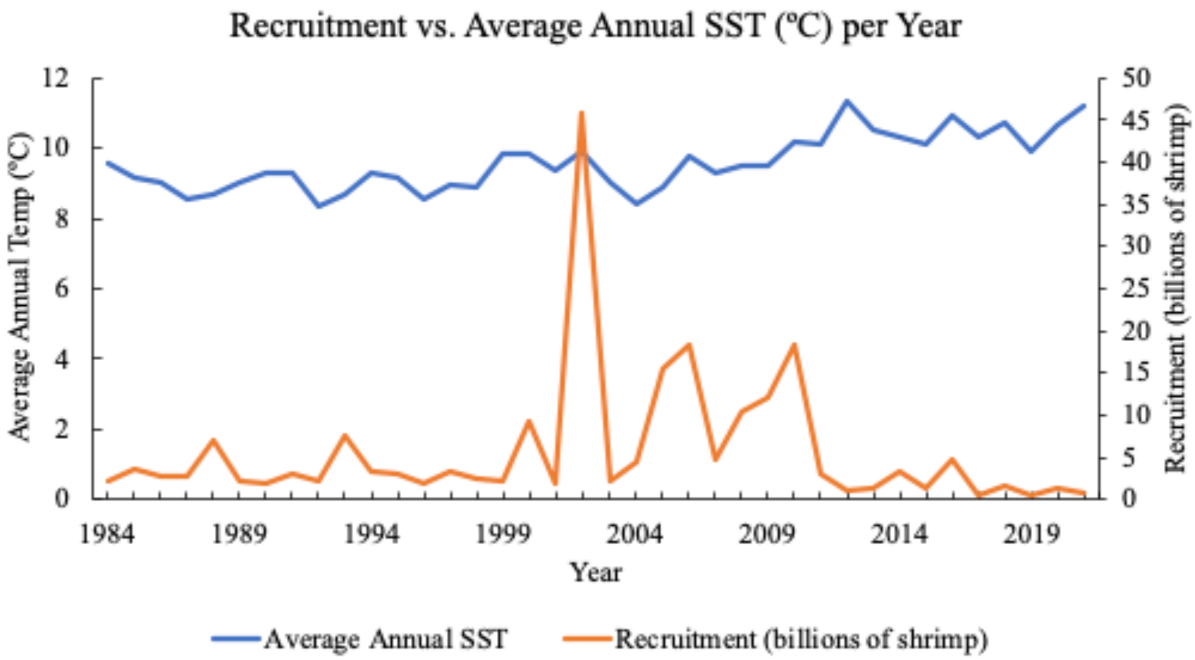
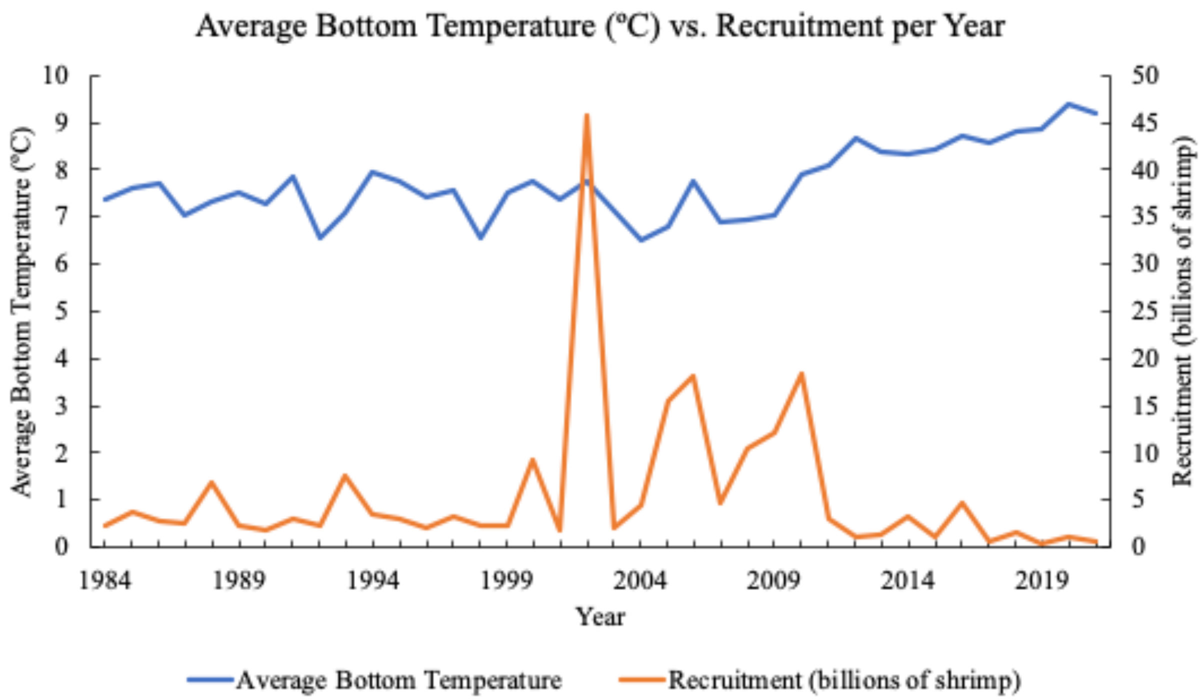
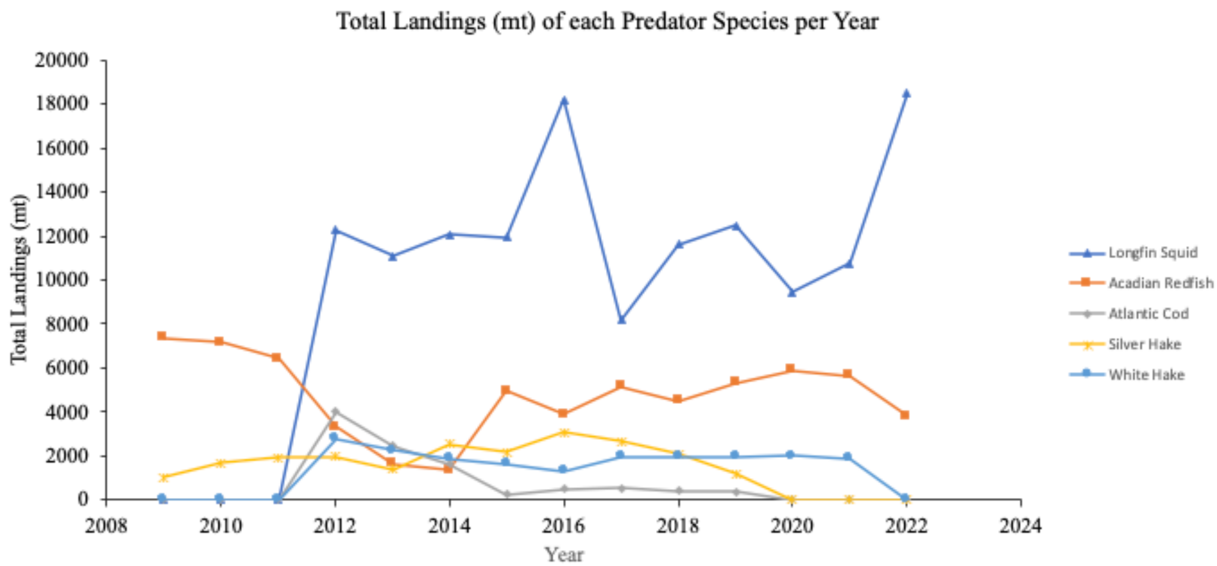
Appendix



Appendix Figure 1. The GOM average annual sea surface temperature (SST) (blue) is on the primary y-axis in metric tonnes and is compared to the recruitment (billions of shrimp) (orange) from 1984 to 2021 on the x-axis. Recruitment was found over a long time frame that measures the amount of shrimp that enter the fishery through immigration and their size and age when they enter. Annual average SST was found by adding up the average SST for each day of the year and dividing it by 365 or 366 days (depending on if it was a leap year or not). SST surpassed 10ºC for the first time in 2011. Recruitment has a high of 45.4 billion shrimp in 2002 but has been close to 0 billion shrimp since 2017.



Appendix Figure 2. The GOM average annual bottom temperature (blue) is on the primary y-axis in metric tonnes and is compared to the recruitment (billions of shrimp) (orange) from 1984 to 2021 on the x-axis. Recruitment was found over a long time frame that measures the amount of shrimp that enter the fishery through immigration and their size and age when they enter. Annual average bottom temperature was extracted from a figure in previous literature about GOM bottom temperature (Charelson, 2020). Bottom temperature surpassed 8ºC for the first time in 2011. Recruitment has a high of 45.4 billion shrimp in 2002 but has been close to 0 billion shrimp since 2017.



Appendix Figure 3. Total landings are on the primary y-axis in metric tonnes over years from 2009 to 2022 on the x-axis. Landings were measured by the ports in the GOM that each fisherman reported per species. The different predator species include Longfin Squid (dark blue), Acadian Redfish (orange), Atlantic Cod (gray), Silver Hake (yellow), and White Hake (light blue).