An Eventful Past Predicting a Bizarre Future: Assessing the Influence of Ocean Circulation on Key Fish Species in Icelandic Waters. An analysis of past circulation records in order to predict the state of demersal fish stocks in future climate scenarios

Matthew Engfer
SIT Study Abroad

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Abstract

Feedback-driven changes in North Atlantic Ocean circulation are affecting marine ecosystems off the coast of Iceland and are predicted to have differing outcomes by 2100. In this study, data reflecting Icelandic fish stock distributions was compiled on a map with oceanographic temperature and depth in order to observe patterns of population changes with changes in ocean currents. After evaluating past temperature effects on demersal fish stocks, future habitat predictions were estimated in weaker ocean circulation scenarios. A number of assumptions were made in order to pinpoint a correlation between ocean temperature and fish habitat. Iceland's unique location and climate offers researchers a chance to analyze changes in marine ecosystems that could see an uncharacteristic drop in temperature. Thus, the purpose of this study is to use maps to make inferences regarding oceanographic patterns, then use the inferences to hypothesize what the future may hold. In this study, fishing data on 4 unique demersal fish species from the past 19 years was compiled on a map in coordination with oceanic conditions within Iceland's waters. A key hope is that future research will delve into studying the magnitude of atmospheric and oceanographic systems in manipulating Iceland's marine ecosystems. With this, more permanent circulation records in the future can shed light on the island's environmental response to changes in climate. In the study, the results revealed that ocean conditions and fish habitats appear to be affected by ocean circulation habits, however it is difficult to accurately predict a future environmental state.

Introduction

Climate change is an inevitable issue that will affect every part of the world. Iceland, a principally ocean-driven island, is no exception. The main question to be addressed in this study is how have demersal fish species responded to changing ocean currents since 2000. A secondary question was how circulation patterns will respond to escalating climate change, therefore painting a picture of fish demographics in Iceland. While statistics calculating the correlation of ocean currents and the locations of fish stocks were not compiled, a hope of the study was that a comprehensive fish stock map could demonstrate annual correlations of temperature. Fish stocks are fish populations that are characterized by their geographic location rather than their biological characteristics (Bonanomi et al., 2015). With examinations of the maps contrived, the maps were recalibrated to show habitat extent with temperature alterations.

The study not only introduces clues for Iceland's climactic future, but it also ponders the potential effects on one of Iceland's paramount industries. Fishing has been one of Iceland's key industries for hundreds of years. It has influenced where people lived, where people worked, and how people perceived their nature surroundings. From the days of first settlement to the mid-20th Century, Iceland's fundamental source of wealth and sustenance ("History of Fisheries"). Even with Iceland's recent hyper-modernization, its swell in tourism, and now-booming infrastructure, the fisheries industry alone still accounted for 6% of Iceland's total GDP in 2019 (Icelandic Chamber of Commerce, 2020). Even without the wealth it generates, fishing remains a centerpiece of culture and livelihood to the people of Iceland. The setting for this study was the waters surrounding Iceland in the country's EEZ (Exclusive Economic Zone), an area that stretches approximately 200 miles from all coastline. Despite Iceland's growth, the EEZ remains rich in nutrients and biodiversity (Icelandic Chamber of Commerce, 2020).

In order to properly appraise the status of fish stocks and populations, a multitude of conditions must be incorporated into a proper ecosystem assessment. For one, oceanographic elements like temperature, salinity, and other chemical factors (i.e acidity) are responsible for alterations in growth and other phenological factors (Sumalia et al., 2011). In addition, primary productivity, nutrients, and other biological factors must also be taken into consideration. Due to the scope of the study, the time constriction, and the lack of data, only temperature was gauged to indicate fish habitat change.

The waters of Iceland are hardly uniform in oceanographic conditions and characteristics. Significant divergence in oceanographic and environmental states of southwest and northeast waters exist that pertain to marine ecosystems and their biodiversity. As exhibited on the survey maps, demersal fish species adapt to the physical and biological variations in geographic location (Sumalia et al., 2011). Often the life cycle of Icelandic demersal fish occurs in coordination with regional changes in ocean temperature and salinity. Due to a lack of knowledge regarding distributions within separate regions, it is difficult to conceptualize a general population shift within the entirety of Iceland's EEZ.

Iceland Hydrology

<u>Currents</u>

Iceland's geographic predicament lays the groundwork for an astonishing case study on the effects of extreme current polarity in the North Atlantic. It sits atop the intersection of the Mid-Atlantic and Greenland-Scotland Ridges and exists in boundary zone of Atlantic and Arctic ocean waters (ICES CIEM, 2018). It is beset in the pathway of warm Gulf Stream currents originating from the eastern United States and cold polar currents originating from the Arctic (Sumalia et al., 2011).

The currents around the Iceland are predominantly temperature and salinity driven, meaning that their movements are powered by regional differences in oceanographic conditions (Sumalia et al., 2011). The mixing of these waters with differing compositions makes for a series of upwelling and downwelling spiraling currents. They are crucial to providing nutrients to the organisms of the marine ecosystem, and a major reason as to why Iceland's waters are so rich in biodiversity (Stefánsson et al., 1991). According to past records, periods of warm ocean water typically stimulate fish population growth due to an expansion in primary productivity (Mason et al., 2021).

The currents patterns within Iceland's waters varies very differently by area. The waters around Iceland are predominated by a set of local cold-tempered and hot-tempered currents. On the

South coast, two smaller currents flow in a circle powered by changes in temperature and salinity. Off the north coast, Arctic polar water mixes with remnants of Atlantic water delivered by the North Icelandic Irminger Current (Sumalia et al., 2011). The North tends to experience larger temperature and salinity variations due to the overbearing influence of Arctic environmental systems (Iceland Meteorological Office, 2018).

The differences of the waters in the North and South of Iceland create a predominant current that circulates *around* Iceland. In both the northern and southern waters of Iceland, mixing of the contrasting water bodies occur. The circulating current around Iceland is vital to transporting heat and nutrients to different marine ecosystems surrounding Iceland. As a result, the Southern and Northern shelf waters in general are both mixing zones of coastal waters and deep-ocean waters (ICES CIEM, 2018).

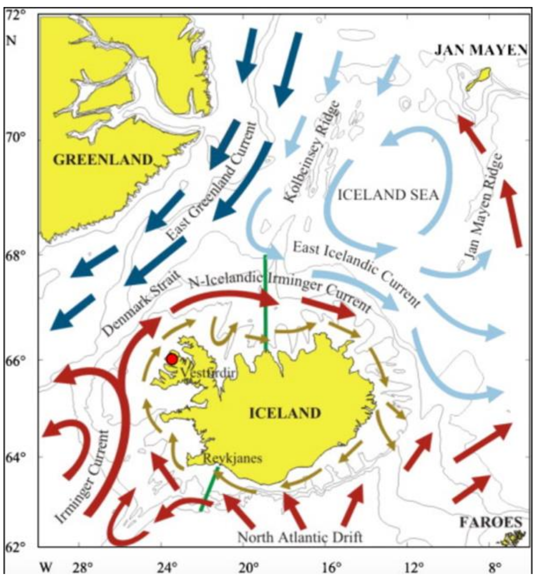
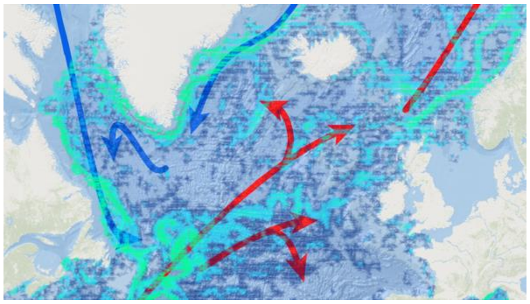


Figure 1: Map of ocean currents around Iceland using coordinates. The colors indicate the temperature of the currents with red being the warmest and dark blue being the coldest. Bathymetric contour lines were included to convey ocean ridges and continental shelves (Astthorsson et al., 2007).

While the smaller currents around Iceland are important, the Gulf Stream, which is powered by temperature and salinity differences in the North Atlantic, is the main driver of the heat to high latitude locations such as Iceland. This current starts in the Gulf of Mexico and ends in upper latitudes of the North Atlantic. As seen in Figure 2, the Gulf Stream branch approaches Iceland and forks off into the N-Icelandic Irminger Current and begins to circulate clockwise around Iceland. The Gulf Stream plays a pivotal role in transporting warmer water to the southwestern coast of Iceland and, as a result, making Iceland's climate more temperate and milder (Stefánsson et al.,1991). Its significance in the North Atlantic is immense to say the least (Carrington, 2021).

Figure 2: Map of Gulf Stream generated on Web ArcGIS. The large red arrows indicate a warm current pattern while the large blue arrows indicate a cold current pattern. The strength of the surface currents were taken from annual mean strength. The light green arrows have a higher velocity than the blue arrows (ESRI).



Significance of the AMOC

When addressing the movement patterns of North Atlantic currents, it is important to acknowledge the presence of Atlantic Meridional Overturning Circulation (AMOC). AMOC acts as an agent of worldwide oceanic movement and is responsible for mild North Atlantic climate conditions and North Atlantic storm systems among other systems (Cheng et al., 2013). The strength of AMOC around Iceland is usually controlled primarily by regional oceanic temperature and density differences. The AMOC powers the Gulf Stream and therefore is responsible for bringing heat to the waters of Iceland. The AMOC is also responsible for transporting cold, deep polar water through the East Greenland Current to the southwest to the Labrador Sea in Canada (Sévellec et al, 2014). In essence, much of the mild climate conditions and high productivity areas around Iceland occur thanks to the presence of the AMOC.

The AMOC is represented in models and graphs as an index. The units are expressed in Sverdrups (Sv), a measurement of the annual mean current velocity at 30°N (Cheng et al., 2013). In simpler words, AMOC index is a reflection of the strength of the circulation's movement and velocity. AMOC typically varies on periods of around 20-30 years in North Atlantic, switching from a strong and weak period (Sévellec et al., 2014). The AMOC has had some regime shifts in the past as seen in Figure _ below. These changes have caused changes the collapse of fish populations. So-called Dansgaard-Oeschger (D-O) events have historically occurred within inter-glacial periods around every 1000 years, resulting in long-term cooling effects that have uprooted marine ecosystems. The warm and cold phases of the DO cycles correspond to periods of AMOC strength and weakening, so they have been the subject of study for climatologists concerned about the future of ocean circulation (Sévellec et al., 2014).

Climate change is predicted to cause lasting effects to the AMOC system in the North Atlantic. Since 1995, scientists have identified a regime shift within AMOC, causing a gradual weakening of the AMOC strength in the Atlantic. Scientists have hypothesized a few potential factors have attributed to this shift. The one predominant factor that has been hypothesized and agreed on by many climatologists is the increased freshwater flux of freshwater into the North Atlantic. Due to this influx, the freshwater significantly reduces the salinity in the ocean and disrupts the Irminger Current from pushing warm water to Iceland. As one might speculate, the majority of the influx of freshwater comes from the Greenland ice sheet. With global warming causing alarming rates of glacial melt, the North Atlantic freshwater influx will steadily rise in years to come (Boers et al., 2021). While the Intergovernmental Panel on Climate Change reports that a regime shift of the ocean circulation is unlikely to occur on its own, it does state that a large influx of freshwater influx could potentially cause a collapse of the AMOC (Boers et al., 2021). Although current ocean circulation models continually disagree about the presence of EWS (early warning signals) that predict an AMOC shutdown event, the likelihood of this scenario may still appear greater than previously thought.

The significant slowing of AMOC, no matter the degree, will signify that less warm water is being transported to the southwest coast of Iceland. With a marine-powered climate, it is very possible Iceland could see a drop in temperature and by some standards be a climate change benefactor. However, a fundamental change in ocean circulation could have profound effects on Icelandic fishing. While cold water demersal fish species such as Greenland halibut might thrive in a cold-watered Iceland EEZ, it is likely that warm-water demersal and pelagic species populations could be desolated and cease to have suitable habitat in much in the high latitudes of the North Atlantic.

Iceland Fish Species

<u>Fish Species</u>

In terms of fish, the unique and nutrient-rich ocean waters around Iceland are home to a variety of fish species. In terms of literal fish, there are demersal species (fish that typically dwell near the ocean floor), flatfish species (demersal fish that have ray-like fins and swim on their side), redfish (deep sea rock and reef dwelling fish), and pelagic fish (small, warm water fish that move in large clusters and migrate long distances) (Ministry of Industry and Innovation).

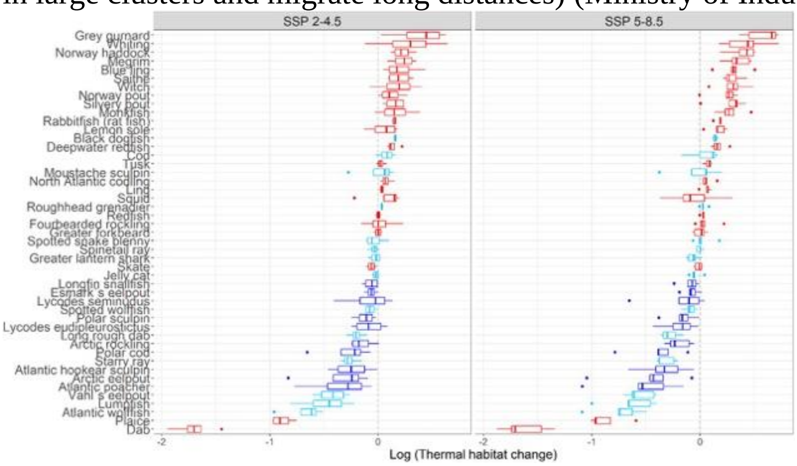


Figure 3: Histogram compiled by researchers at the Marine and Freshwater Institute. The box plots are representations of thermal habitat suitability change for the future years 2061-2080 based on a 2000-2018 record. The plots are divided into two separate SSP (future anthropogenic socioeconomic climate responses) scenarios and the x-axis depicts a total change in suitable habitat. Boxplots for the fish species are subdivided by color based on their temperature preferences (Mason et al., 2021).

In this study, the intended focus was on three demersal fish species and one flatfish species. Demersal species and flatfish species tend to be easier to map because their Icelandic populations are often more established and more permanent than pelagic fish (Mason et al., 2021). The species were chosen predominantly based on the depth and temperatures of their habitat. In Dr. Woods' scientific article, researchers divided up various Icelandic fish by their ocean temperature preferences and measured the effect of climate change on their total habitat area (Mason et al., 2021). Based on this, species were chosen with the hopes of being capable of generally summarizing the responses of all Icelandic fish that are relevant to Iceland's fish industry.

The first fish species that is the subject of the study is *Molva dypterygia*, or Blue ling. Blue ling is a shallow, warm water fish that is found almost exclusively along south coast and to the southwest of Iceland. Typically caught at a depth of about 80 meters, it is found at predominantly sandy bottoms near coastline. This fish species saw a peak population amount around 2010 but has since declined in Iceland's waters ("Blálanga *Molva dypterygia*", 2021). The change could be attributed to current AMOC weakening and decrease in temperature in the southwest of Iceland. Comparative to the other species of fish, Blue ling is not as popular and has no historical significance to Iceland. However, due to its hyperdynamic population fluctuations and its new appearance in the region in recent years, Blue ling is an important fish to study when addressing climate change.

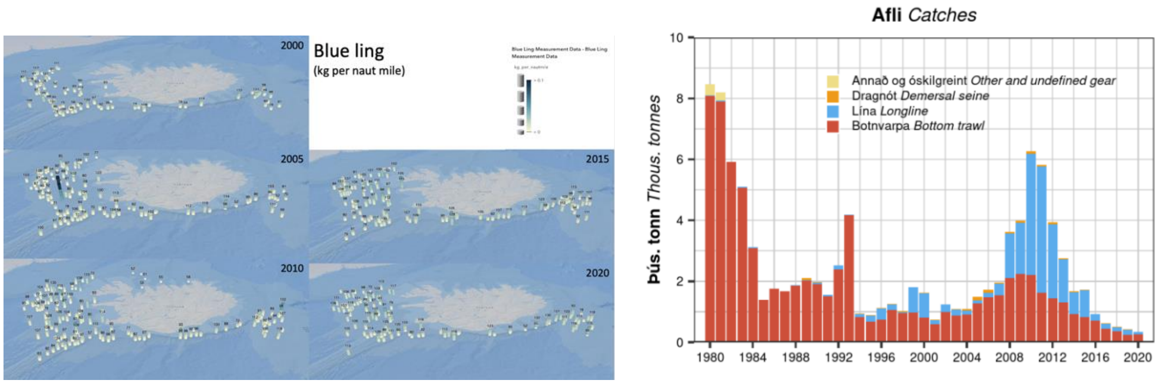


Figure 4: The map (left) was generated using ArcGIS Online, the data was provided by the MFRI bottom trawl survey. The amounts of Blue ling catches were measured in kilograms per nautical mile and the heights and colors of the cylinders correspond with kg per naut mile value (ESRI). The graph (right) details the total annual catch of Blue ling (above) and the proportion of the catches divided by fishing technique using color coding. The graph was created by the Marine and Freshwater Institute with data from fisherman catch diaries (State of Marine Resources and Advice 2021, 2021).

The second fish species that is focused on in the study is *Gadus morhua*, otherwise known as Atlantic cod. Atlantic cod is a cold-water fish that typically lives at depths of approximately 200 meters, but depths range substantially. It is extremely abundant; it is found in all regions of Iceland. The densest populations appear to the north and northwest of Iceland. It is by far Iceland's most popular fish ("Þorskur *Gadus morhua*", 2021). Atlantic cod is known for its versatility and tenacity, making it able to thrive in various ocean environments. This fish species will likely dominant and stable even with widespread fluctuations as part of climate change, only harsh changes could derail Atlantic cod's ecological dominance.

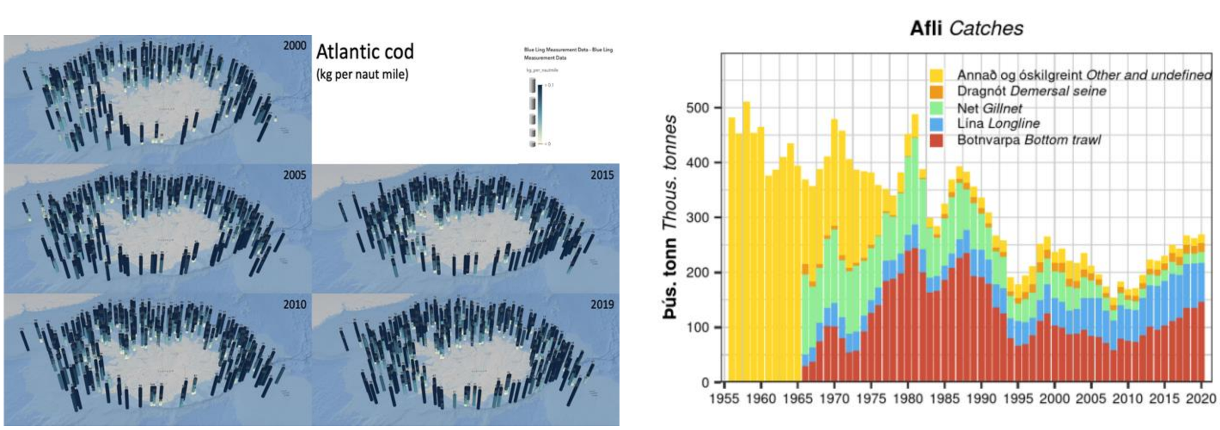


Figure 5: The map (left) was generated using ArcGIS Online, the data was provided by the MFRI bottom trawl survey. The amounts of Atlantic cod catches were measured in kilograms per nautical mile and the heights and colors of the cylinders correspond with the kg per naut mile value (ESRI). The graph (right) illustrates the total catch of Atlantic cod in thousand tons

from 1955-2020. The graph was compiled by the Marine and Freshwater Institute in the 2021 Marine Resources Assessment & Advice Report. The bar graphs are color-coded by separate technique procedures due to Atlantic cod's wide popularity (Þorskur– Cod, 2021) .

The third fish species that is focused on in this study is *Reinhardtius hippoglossoides*, commonly known as Greenland halibut. A more infrequent fish than Atlantic cod, Greenland halibut is a cold water, bottom-dwelling fish typically caught at depths of around 800 meters. The main fishing stocks are predominantly on the far northwestern edge of Iceland's exclusive economic zone ("Grálúða *Reinhardtius hippoglossoides*", 2021). Greenland halibut is unique because its stock is assessed as a population found in Icelandic, Greenlandic, and Faroese waters ("Grálúða *Reinhardtius hippoglossoides*", 2021). While Greenland halibut stocks have been relatively consistent in recent years, fears have grown that an increase in ocean temperature could cause them to relocate far north of Iceland.

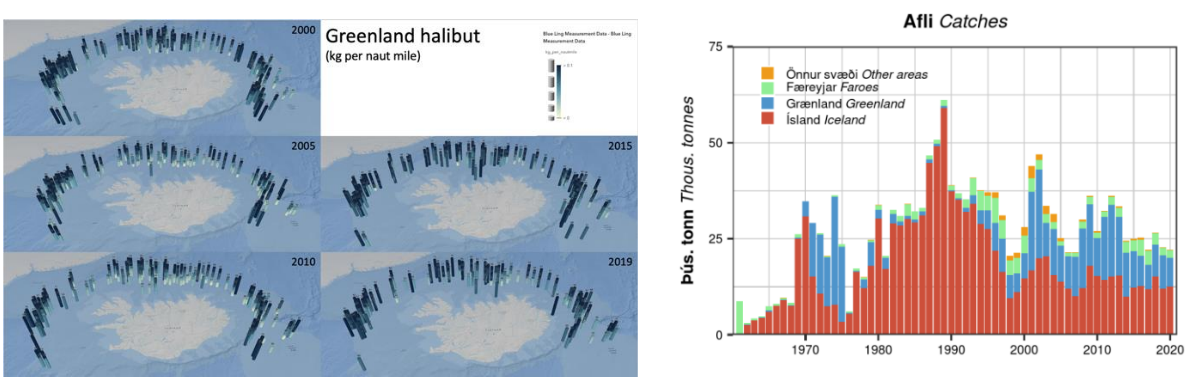


Figure 6: The map (left) was generated using ArcGIS Online, the data was provided by the MFRI bottom trawl survey. The amounts of Greenland halibut catches were measured in kilograms per nautical mile and the heights and colors of the cylinders correspond with the kg per naut mile value (ESRI). The graph (right) measures total annual catch in thousand tons over the past 50 years or so. Unlike the graphs, the differences in color represent the different regions of Greenland halibut stocks. Because of their temperature and depth preferences, halibut linger in deeper, largely international waters (Grálúða – Greenland Halibut, 2021).

The last fish species that is covered in the study is Anarhichas lupus, otherwise known as Atlantic wolffish. Atlantic wolffish is a cold-water demersal fish typically found right outside the Westfjords in northwest Iceland. Atlantic wolffish prefers cool waters and is typically caught at a depth of 200 meters. Catches of wolffish in Icelandic waters have been stable the past 10 years or so ("Steinbítur *Anarhichas lupus*", 2021). In the future, Iceland may see an increase in wolffish populations that live in closer proximity to land if temperatures decrease.

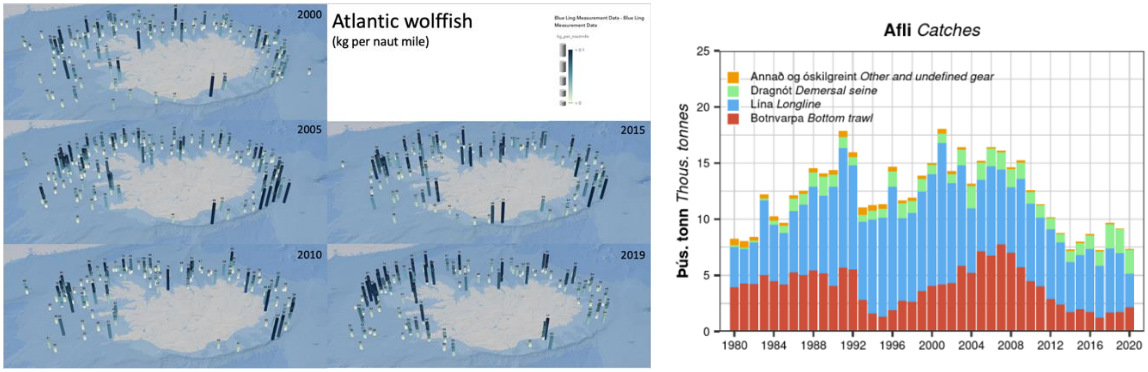


Figure 7: The map (left) was generated using ArcGIS Online, the data was provided by the MFRI bottom trawl survey. The amounts of Atlantic wolffish catches were measured in kilograms per nautical mile and the heights and colors of the cylinders correspond with the kg per naut mile value (ESRI). The graph (right) illustrates the total catch of Atlantic wolffish in thousand tons over the past 40 years. The graph was compiled by the Marine and Freshwater Institute in the 2021 Marine Resources Assessment & Advice Report. The bar graphs are color-coded by separate fishing technique procedures ("State of marine resources and advice 2021", 2021).

Methods

The following study is a series of maps generated on an online geographic information systems (GIS) webservice called ArcGIS designed by ESRI. The data inputted into the maps was a 23-year record of autumnal bottom trawl surveys from 1996 to 2019 executed by a research team at the Marine and Freshwater Institute of Iceland. It is conducted every year in the month of October by a research vessel that circles Iceland and travels to geolocated stations at specific coordinates. Measurements entail releasing a scientific bottom trawl net over a certain distance that catch and count fish while also collecting environmental information. At these station points, ecological, environmental, and statistical information was recorded by researchers and put into a CSV file. In total, around 220,000 data entries across the fish species Blue ling, Atlantic cod, Greenland halibut, and Atlantic wolffish from 1995 to 2019 were provided for the study. For the limited scope of this project, only the points measuring kilograms per nautical mile, bottom temperature, depth at the beginning of the bottom trawl, and coordinates were used in the GIS-created maps.

When generating a map of individual species' Icelandic stocks, the coordinates were plotted to show the locations of the trawl stations. The data was filtered by specific species and then filtered again to show population extents in the years 2000, 2005, 2010, and 2019. The measurements of kilograms per nautical mile and the lengths of the fish were provided at each of the individual within each of the given years. Using the SceneViewer display on ArcGIS Online, cylinders were created for individual data points to indicate the weight of the catch per nautical mile. A standardized scale of 0-0.1 kg per nautical mile was used across all maps to accurately illustrate differences in total catch between species and years.

When generating the Iceland Bottom Temperature maps, station points with cumulative data across all fish species filtered by year were plotted onto a map. Under the analysis option in web ArcGIS, the bottom temperatures from individual points were interpolated onto a map through the "interpolate points" function. The scale was created with ranges of 2°C in order to properly demonstrate change between years. A similar procedure was followed when generating the

Iceland Bottom Trawl Depth map of Iceland. Cumulative fish data across all years was compiled onto a singular map, then the points were interpolated using the Analysis GIS function. The attribute used was the beginning of the bottom trawl depth. Although not the actual depth, because demersal and flatfish species dwell near the bottom of the waters they live in, an assumption was made that the depth of the trawls is a relatively accurate depiction of the legitimate bathymetry surrounding Iceland (Ministry of Industry and Innovation). In addition, the map was color-coded to have the deepest points throughout the time record overlay the shallower points, and so the maximum trawl depths should provide some indication of the depth extent at the following coordinates. The depth scale was designed to rise exponentially by a multiple of 2 per range in order to more accurately depict the topography of the shallow waters near the coastline while also encompassing depth maximums.

For the Depth & Bottom Temperature maps, data was filtered by year and species and plotted into Web ArcGIS. The attributes bottom temperature and beginning of trawl depth were connected and circles with color were created for each point to exemplify both values. Uniform scales for temperature and depth across all maps were created to show proportional differences across species and years.

The future climate prediction maps were mapped through a different and more elaborate process. The temperature climate scenarios were inferred based on knowledge gained from AMOC model articles. First, an identical layer with the cumulative fish data across all years was produced in Microsoft Excel and individual bottom temperature points were amended and recalculated with the specified temperature change. These amended cumulative data sheets with different temperature adjustments were submitted into Excel as future temperature prediction data. Next, the original data sheet was divided into fish species and each titled with the name of the species. Using Excel’s spreadsheet calculator, standard deviations for bottom temperatures across all years for each species were calculated. With the standard deviations for each species calculated, a range 1 standard deviation away in both directions was designed in order to summarize the average temperature and, in essence, habitat suitability for each fish species. After that, the “find similar locations” option under the analysis function was implemented. The “find similar locations” function correlated bottom temperature points from the original data sheet with the new bottom temperature points from each of the future prediction data sheets. Before undergoing the calculation, it is important to include that the original data sheet was filtered to include points within the habitat suitability range and from the year 2019 (to get the most relevant information). The calculation product was the same set of station points but measuring the correlation of the habitat suitability temperature range and the ocean temperatures for the future scenarios with SimilarityRank. The last step was to use the analysis function to interpolate the correlation points using their sum squared value differences (attribute calculated automatically by ArcGIS). The finished product is a set of maps that depict the areas of high and low habitat suitability for different fish species. The ranges for sum squared value differences contours were calculated automatically by ArcGIS and differ by year and species, but they still properly reflect population distributions.

When mapping data and making conclusions, quite a few assumptions were made when designing this study. First, the data points collected in the MFRI autumnal survey do not reflect the amount of fish actually caught, they are simply areas that reflect fish stocks of Icelandic demersal species. However, they are taken with prior knowledge of fish stock locations and so they serve as a quite viable source of information on fish demographics. In addition, as mentioned before, the depth points used are not the actual measurements of depth but they do serve as reliable indicators of fish population depths and changes in ocean temperature. In terms of AMOC predictors, determining the exact influence of freshwater flux on AMOC strength remains debated, let alone how it will affect ocean temperatures around Iceland (Boers et al., 2021). The basic temperature amendments serve as placeholders for potential future scenarios, and are simply designed to show how fish respond to different temperature changes.

Results

Bottom Temperature and Depth Study

Using data provided by the MFRI autumn bottom trawl survey, a set of maps depicting changes in bottom temperature, trawl depth, and kilograms of catch per square kilometer were created. After generating the maps, some basic analysis on visible trends was written below.

The first map generated displays a temperature map and a depth of Icelandic waters for the years 2000, 2005, 2010, 2015, and 2019. The temperature map is to be used as a reference for overall temperature change and population fluctuations over the 19-year record.

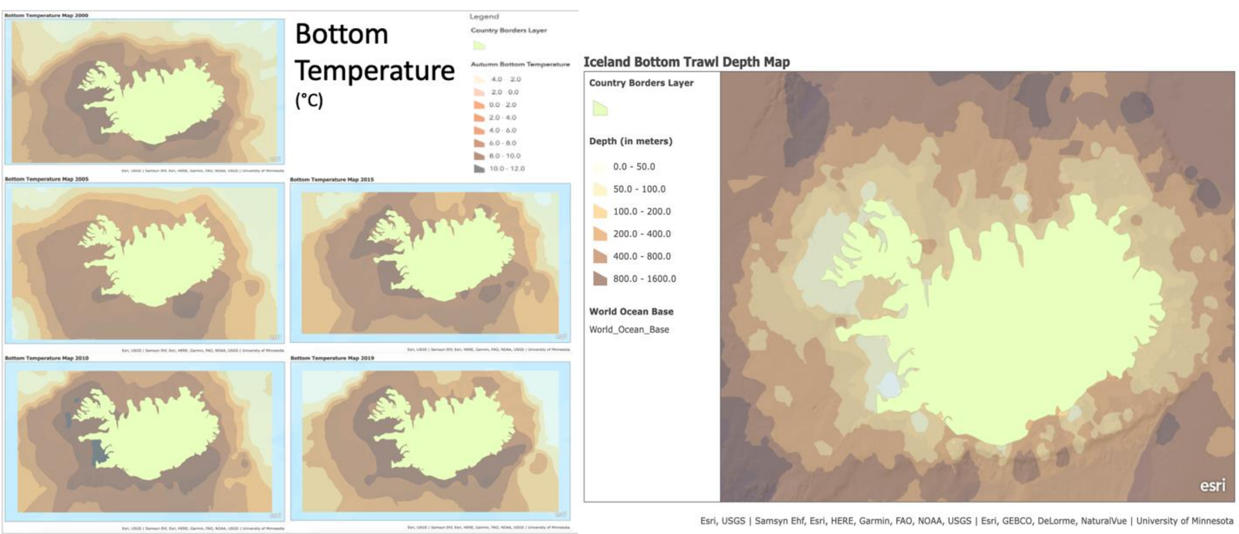


Figure 8: Both the series of the bottom temperature maps on the left and the depth map on the right were generated in ArcGIS online using the MFRI bottom trawl survey data. In the temperature maps, bottom temperature data points for 5 separate years were interpolated onto a map. On the maps, the darker the area color signifies a higher the temperature range. On the left, the depth data points of the bottom trawl beginning were interpolated onto a map with darker colored areas signifying a greater depth (ESRI).

According to the maps created, bottom temperature is relatively consistent with periodic but natural fluctuations on a period of about 5 years. One main observation is that while the locations of extreme highs fluctuate, the waters to the South and West regions remain mostly warm and unaltered. The following observation is a reflection of the Gulf Stream's influence on Iceland's southwest region. The variations across years seen could either be attributed to natural fluctuations or long-term climate effects.

The northeast region, on the other hand, consistently differed from the southwest in that a more severe drop in ocean temperature occurred closer to land. Unlike the gradual temperature gradient that exists in the South, the Northeast edge of the continental plate drops off quickly. This could be attributed to a steeper northeast continental shelf drop but the most likely reasoning is that the region is inherently colder than the southwest due to the influence from the Arctic Ocean. Overall, the similarities reflect prior knowledge about current mixing and the Irminger Current's influence within Iceland's waters.

Despite similarities, a few trends can be observed over the measured 19-year period. For one, a westward expansion of warmer temperatures occurred off the western coast of Iceland from 2000 to 2010. The record reached an approximate peak of warm temperatures by the year 2010, as conveyed with the presence of 10-12 °C areas off the west coast. Since 2010, however, there has been an evident but small decrease in ocean temperature, perhaps due to the early presence of AMOC weakening or fluctuations in the regional atmospheric conditions.

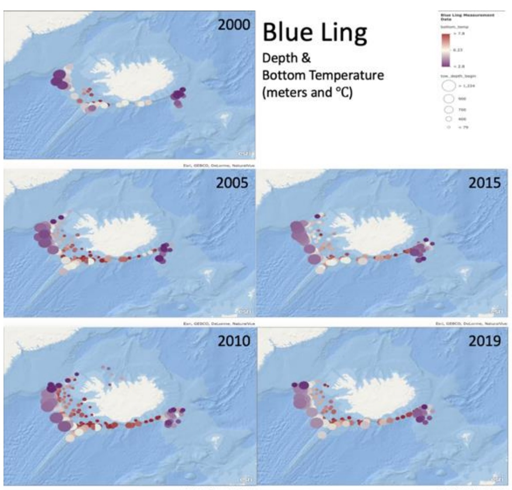


Figure 9: The series of maps describing the population centers of Blue ling fish stocks in 5 separate years were created through ArcGIS Online using the MFRI bottom trawl survey data. Using color to measure temperature and circle sizes to indicate depth, data points were plotted to show Blue ling population extents over time (ESRI).

<u>Blue Ling</u>

Maps of Blue ling catches indicate a major expansion of population size from the year 2000 to 2010. What starts as a couple of isolated deep, cold water populations in 2000 rapidly develops into an established population by 2010. During peak population in 2010 saw Blue ling dwelling in typically warmer temperatures of mixed depth off the Western coast and a singular pocket of fish in the Southeast. Since 2010, the population has slightly weakened to a stable but not ecologically dominant state.

The rapid rise of Blue ling in Iceland's waters can likely be attributed to the warming of the North Atlantic due to radiative forcing. Since 1995, the ocean has seen a considerable rise of temperatures that, until 2016, have been well above the average from the past century (Boers et al.). The slight weakening of the population after 2010, however, could be an early signal of AMOC weakening and GIS freshwater flux.

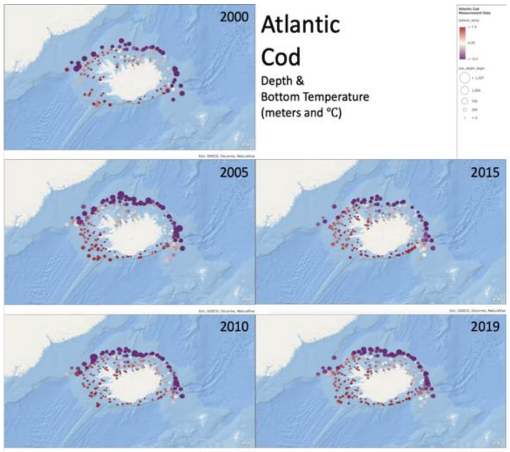


Figure 10: The series of maps describing the population centers of Atlantic Cod fish stocks in 5 separate years were created through ArcGIS Online using the MFRI bottom trawl survey data. Using color to measure temperature and circle sizes to indicate depth, data points were plotted to show Atlantic Cod population extents over time (ESRI).

<u>Atlantic Cod</u>

Maps of Atlantic cod reveal a few details regarding temperature and depth trends. Although the changes aren't visibly obvious, it is possible to see a buildup of Atlantic cod populations in Iceland's eastern and northeastern waters. Additionally, a strengthening of populations appears in temperatures areas off the west coast over the 19-year record. Lastly, the south coast sees a slight uptick of shallow, warm-water cod survey locations, as well.

Overall, the Icelandic Atlantic cod fish stock has remained quite stable, if not improved, according to the 19-year record. The successes of Icelandic Atlantic cod populations probably serve as a testament to the species' adaptability and considerable fish quota enforcement efforts by the Icelandic government. Atlantic cod is indispensable to the Icelandic fishing industry, so the population is well researched and maintained. Additionally, Atlantic cod is a flexible species that can adapt to almost all the waters around Iceland. Any negative changes that were identified were likely a reflection of slight environmental variations rather than a momentous shift in cod population dynamics. The small increases in the south and west could possibly be explained by an expansion of Atlantic cod into warmer waters in order to have less competition for resources. In the complete opposite case, the slight density increase of Atlantic cod populations in the northeast could be a single example of temperature-induced population migration. Overall, however, the cod stock remains relatively unchanged and only far-reaching oceanic changes will impact stocks.

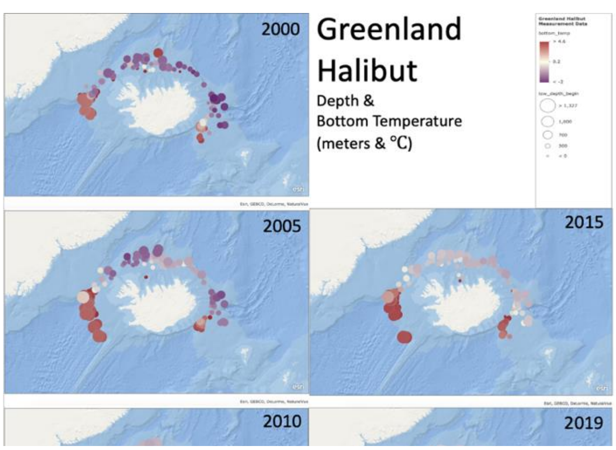


Figure 11: The series of maps describing the population centers of Greenland halibut fish stocks in 5 separate years were created through ArcGIS Online using the MFRI bottom trawl survey data. Using color to measure temperature and circle sizes to indicate depth, data points were plotted to show Greenland halibut population extents over time (ESRI).

<u>Greenland Halibut</u>

Maps of Greenland halibut reveal some striking evidence for climate variation in the North Atlantic region. From 2000 to 2019, the Greenland halibut population points found in the northern and eastern waters of Iceland experienced an apparent increase in bottom temperature. One peculiar observation was that Iceland populations on the west and east coasts form a solid population cluster with a maximum southward extent around 2010. 2010, according to the temperature maps created, witnessed by far the warmest temperatures comparatively to other years on record.

Although the amount of Greenland halibut caught has remained quite consistent in recent years, the conditions at which they are caught have changed ("Grálúða *Reinhardtius hippoglossoides*", 2021). However, Greenland halibut catch locations demonstrate that the species prefers its ideal depths over its ideal temperatures. For example, while temperature increased in both the south and north, the size of depth symbols remained constant, signifying that halibut remained at the same depths despite large temperature differences.

The changes in ocean temperature of the trawl stations were very significant, nonetheless. The increase in temperature could be due to an increase in relative ocean temperature in the Arctic Ocean. An increase in albedo due to ice sheet loss and atmospheric radiative forcing could be two attributing factors to that change.

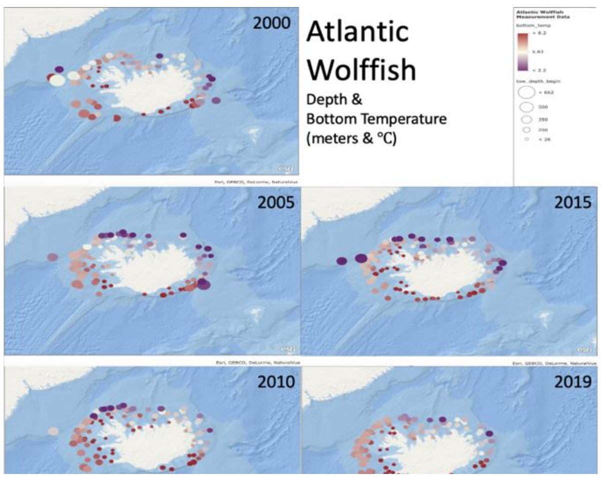


Figure 12: The series of maps describing the population centers of Blue ling fish stocks in 5 separate years were created through ArcGIS Online using the MFRI bottom trawl survey data. Using color to measure temperature and circle sizes to indicate depth, data points were plotted to show Greenland halibut population extents over time (ESRI).

<u>Atlantic Wolffish</u>

Maps of Atlantic wolffish have shown a unique population development over the 19-year record. Starts with locations of warm and cold with varying depth in 2000, the wolffish fish stocks have grown to stable and consistent. The population clusters in the north are typically cold and cool waters close to the coast, while the population clusters in the West are warmer but farther from the coast. One negative observation is that the cold-water populations spots in the East started to disappear. Overall, wolffish stocks have moved landwards and to more warm waters.

The changes from 2000-2010 in Atlantic wolffish population locations in the west could be accredited to ideal habitat conditions closer to the coast. The strengthening in the North is possibly influenced by a movement of fish from cold to cool waters. Since 2010, however, the chain along the northwest coast started to distance itself from the coast. Based on the physical information presented, it appears that Atlantic wolffish enjoys the zones of mixing waters. Like cod, wolffish is an adaptive cool-water fish that could thrive in either Arctic or Atlantic-dominated ocean waters.

AMOC Prediction Study

Ocean circulation is far from a static system. Global warming has caused and will increasingly cause ocean circulation to change rapidly. With increasing atmospheric temperatures due to growing concentrations of greenhouse gases, When the freshwater enters the ocean in the Irminger Basin, it significantly slows the warm water spread to coastal Europe.

Weakening of the AMOC since the regime shift in 1995 has already accounted for circulation disruptions in North. For one, the observed "cold blob" around 40°N in the Atlantic is a result of freshwater flooding into the path of the Gulf Stream. When this foreign water enters into the Gulf Stream, it hinders movement by preventing cold water from sinking to the bottom of the ocean. With an increase in glacial melt, it is very reasonable to expect this cold blob to grow in magnitude and intensity (Keil et al., 2020).

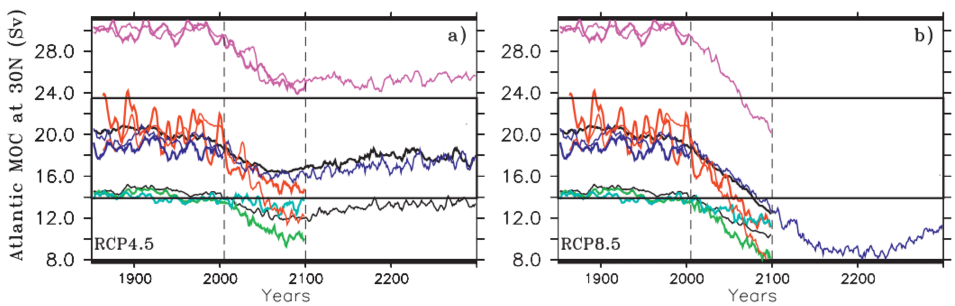


Figure 13: The following graphs picture AMOC weakening projections using ensemble models from RCP 4.5 and 8.5 climate scenarios. The MOC value on the y-axis represents the AMOC stream-function value expressed as a annual-mean heat transport value (Cheng et al., 2013).

Actively studying AMOC strength and the weakening that has occurred over the past century is a very new field of study. In fact, the AMOC record only stretches back to 2004 (Bellomo et al., 2021). Before that, climatologists had to rely on deep ocean sedimentary records to observe AMOC fluctuations (Boers et al., 2021). While it has been strongly theorized that AMOC strength and freshwater flux have a convincing negative relationship, AMOC climate models have varying predictions about the future. Using CMIP-5 and CMIP-6 models, ocean current projections have been compared to determine the best fit future for AMOC circulation (Bellomo et al., 2021). Further climate model predictions have large deviations, and remain uncertain even in the most modern research studies.

In this study, we will look at three separate future climate scenarios. They are all unique in their timing, severity, and environmental implications. Both the RCP 4.5 and RCP 8.5 model simulations predict a further decrease in AMOC strength until at least 2100. Apart from that, the scenarios differ greatly and major generalizations regarding ocean temperature were made due to the models' inconsistency.

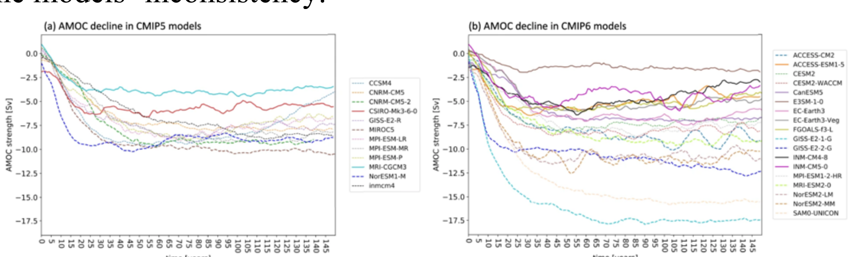


Figure 14: A pair of graphs that predict annual-mean AMOC strength anomalies at 26.5°N in the future. The model projections were made using a 10-year running mean. Thick dashed lines signify large AMOC decline scenarios while the solid lines signify small AMOC decline future scenarios (Bellomo et al., 2021).

Scenario 1- CMIP-5 RCP-4.5 Models: Minor Weakening of AMOC Event

The first scenario is AMOC strength weakening but to a lesser degree. In order to simplify some confusion regarding climate models, an RCP 4.5 outcome was attached to the series of CMIP-5 models. In a RCP4.5 scenario using CMIP-5 models, the predicted decrease in AMOC strength remains controversial. CMIP5 predict decreases anywhere from 4 Sv (-27%) to 10 Sv (-58%) by around 2100 (Bellomo et al., 2021). No matter the potential outcome, the weakening that could occur in this scenario is still significant and will likely have widespread effects in Iceland's marine ecosystems. In any case, however, it still remains a challenge predicting what sort of temperature fluctuations will be felt in Iceland's waters.

Given the unpredictability of 4.5 scenarios, a mock model was produced. Because of the differentiation of climate models, it will be assumed that temperatures around will *all* increase by 1°C. An increase in 1°C was generally estimated because a 4.5 scenario predicts a less extreme AMOC weakening. Given this, rapidly increasing ocean temperatures will prevail over North Atlantic cooling so the temperature will generally rise about 1°C by 2050.

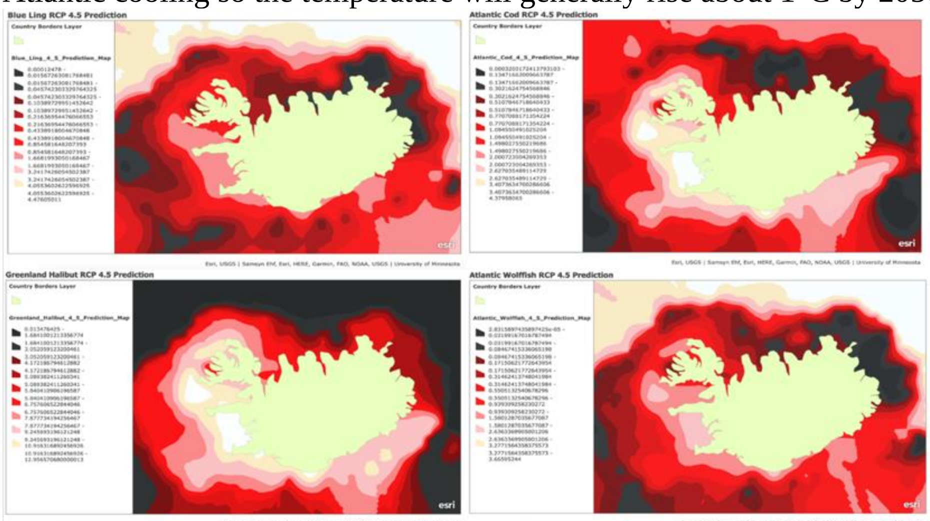


Figure 15: The following are a series of ArcGIS Online generated maps that measure habitat suitability likelihood based on differences between 2019 bottom temperature data points and amended data points from 2019 with a 1°C increase in bottom temperature. The sum squared value differences between the different temperature data sets were interpolated onto a map with ranges representing the correlation between the two temperature scenarios (ESRI).

Scenario 2- CMIP-5 RCP-8.5 Models: Major Weakening of AMOC Event

In the RCP 8.5 Scenario using CMIP-6, an increased amount of AMOC weakening creates different changes to fish populations. In this scenario, it is likely that large amounts of weakening ocean circulation will slightly outweigh the rapidly increasing temperature of the oceans from climate change. In some models, a weakening from an 8.5 RCP scenario can range anywhere from a decrease of 1.5 Sv to 30 Sv by the year 2050 (Bellomo et al., 2021).

Much like the 4.5 RCP models, there is a lot of inconsistency between models so it is hard to accurately determine a temperature change within Iceland's waters. However, a very rough estimate predicts a decrease of 0.5°C. In this instance, strong Gulf Stream weakening would produce a stark cooling of Icelandic waters, cancelling out the significant ocean warming happening worldwide. While the 0.5°C decrease may seem miniscule when visualizing total

AMOC weakening, the temperature change is still significant and will likely have other, more severe ecological shifts.

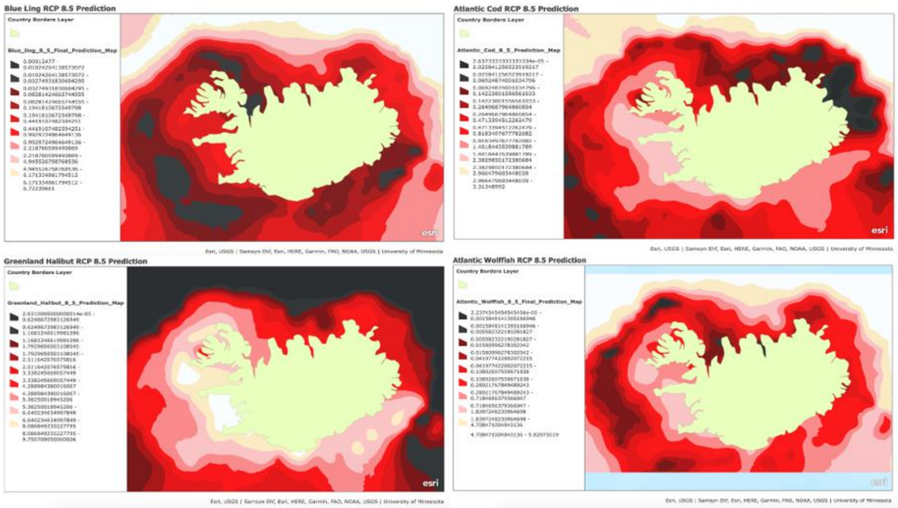


Figure 16: Figure 17: The following are a series of ArcGIS Online generated maps that measure habitat suitability likelihood based on differences between 2019 bottom temperature data points and amended data points from 2019 with a 0.5°C decrease in bottom temperature. The sum squared value differences between the different temperature data sets were interpolated onto a map with ranges representing the correlation between the two temperature scenarios (ESRI).

<u>Scenario 3- CMIP-5 RCP-8.5: AMOC Shutdown Event</u>

This is the worst-case scenario. While determined "unlikely to occur in 21st century" in the recent IPCC report, it is certainly still possible. Scientists hypothesize that a sudden, major melting event on the Greenland Ice Sheet could spur a Gulf Stream collapse. In the year 2021, news articles such as credible platforms such as The Guardian among others hint at a potentially imminent Gulf Stream shutdown (Carrington, 2021). As observed in past ocean sedimentary records, the point of bifurcation (point of system collapse) occurs when a large surface freshwater flux enters the North Atlantic in the ocean west of Greenland (Boers et al., 2021).

In this scenario, the cold waters around Iceland, which typically circulate around the island will predominantly remain in place; the mechanism to its circulation has failed. The decrease could be quite significant, but, per usual, it is hard to determine an exact estimate. Based on how rapid ocean circulation changes are and given Iceland's proximity to the Greenland Ice Sheet and the Arctic Circle, a rough estimate would be a 3°C decrease.

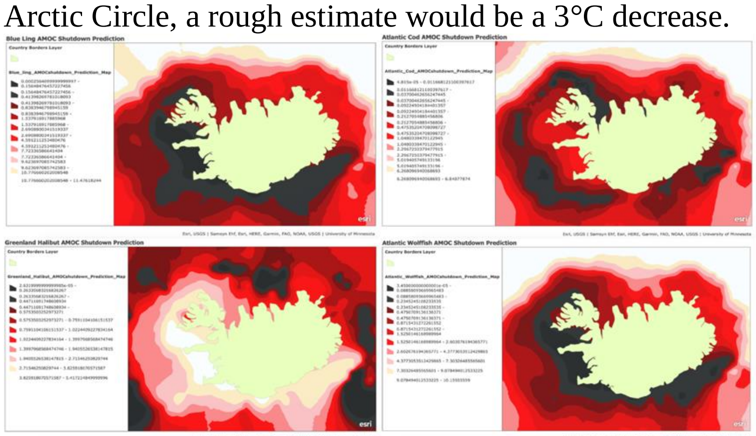


Figure 18: Figure 19: The following are a series of ArcGIS Online generated maps that measure habitat suitability likelihood based on differences between 2019 bottom temperature data points and amended data points from 2019 with a drastic 3°C decrease in bottom temperature. The sum squared value differences between the different temperature data sets were interpolated onto a map with ranges representing the correlation between the two temperature scenarios (ESRI).

Analysis

Reflection on Bottom Temperature & Depth Study

After physically observing and analyzing the GIS-generated maps, it is apparent that fish stocks have not moved in concurrence with changes in oceanic circulation from 2000 to 2010. The populations themselves, however, do lie in coordination with the traditional pathways of currents. Blue ling, a warm-water fish thrived in the southwest waters of Iceland, directly in the path of Gulf Stream warm water. Atlantic cod and Atlantic wolffish, cold-water demersal fish, mingled in areas of heavy Atlantic and Arctic ocean mixing. Greenland halibut has historically shifted between areas near the Irminger and East Greenlandic Currents depending on habitat suitability ("Grálúða *Reinhardtius hippoglossoides*", 2021).

With many assumptions made, there were a few inter-record trends that should be mentioned. For one, the area of warm temperature in the Southwest rises and contracts over the record. With this, all of the fish surveys reflect this change at least to some extent. According to many sources, the warm, Atlantic waters have dominated Arctic waters off the coasts of Iceland, providing evidence for a temperature increase in past decades. In the Blue ling record, the population pockets remained in the warmest part of the country as they settled in Iceland's waters. Following a similar trajectory, the maximum population extent was in 2010 and remains concentrated in the warm waters to the south of Iceland.

Reflection on AMOC Prediction Study

After creating the AMOC prediction maps, some fascinating observations can be made. While only being a simplified and one-sided future prediction, a lot of inferences were fabricated through physical observation.

In the CMIP-5 RCP 4.5 simulation, the 1°C increase forced some quite unlikely shifts. For the Blue ling populations centralized in the southwest, the temperature increase resulted in an outward expansion of Blue ling habitat suitability. The species could actually thrive in southern and western Iceland in the RCP 4.5 simulation. For Atlantic cod, the RCP 4.5 simulation saw the movement of population clusters to the northeastern coast, interestingly enough. With a 1°C increase, cool and relatively shallow waters become sparser, and so Atlantic cod may need shift to these areas in order to succeed ecologically. Greenland halibut population centers in the RCP 4.5 scenario move away from land in the north waters from Iceland. This major change is major because it is quite likely that Greenland halibut venture out of the EEZ into international waters in order to seek suitable habitat. Atlantic wolffish exemplified similar tendencies to Atlantic cod with northeast similar population centers. In addition, Atlantic wolffish populations in the southwest are able to thrive far away from land with a uniform 1°C increase in ocean temperature.

In the CMIP-6 RCP 8.5 simulations, the habitat suitability maps look quite different. For Blue ling, the populations around the country weaken and their populations become predominantly centralized to the southwestern region of Iceland. Atlantic cod populations are spread equally around Iceland and form a thick, solid ring on the map existing a considerable distance from shore. Interestingly enough, the map depicting Greenland halibut habitat suitability in the RCP 8.5 scenario is almost identical to the map in RCP 4.5 scenario. The lack of differentiation illustrates a theme that Greenland halibut populations are often rooted to specific geographic locations despite minor temperature discrepancies. Atlantic wolffish in the RCP 8.5 scenario saw a shift westward shift of populations in the north and a contraction of the southward extent of habitat off of the southwest coast.

In the AMOC Shutdown event, major demographic changes for all 4 fish species transpires. For Blue ling, a 3°C decrease creates a hypercontraction of population that confines the species to the warm and shallow waters along the south and western coast. For Atlantic Cod, the major temperature decrease results in a westward shift away from the previous centers in the north and northeast waters. While a large amount of area remains inhabitable for Atlantic cod, a 3°C decrease forces the species to migrate to ocean that is dominated by warmer Atlantic ocean water. After a significant temperature decrease, Greenland halibut population clusters in the north and the east finally start herding towards Iceland, if not weighed down by depth limitations. Lastly, Atlantic wolffish will see a severe relocation to the warmest waters of Iceland along the south coast in an AMOC shutdown model simulation. Overall, the simplified predictions allow for the viewer to visualize a common trajectory path for fish species as the temperature continues to drop.

Discussion

The reality is that climate model predictions vary too greatly to be observed. One limitation to modelling accurately modelling AMOC is that the record measuring its strength has only been around for a short period of time. Another limitation is that scientists have unintentionally overlooked the state of ocean circulation and instead have focused on ocean temperature and sea level rise; pressing matters that are presently affecting coastal regions all over the world. Due to Iceland’s unique situation, warming waters are not causing an immediate threat to the island. Thus, only until recently, a lack of research regarding North Atlantic currents has created a knowledge vacuum regarding Iceland’s fisheries and marine ecosystems. Studying the influence of the unique ocean circulation controlling Iceland, however, could reveal important details regarding the future of Iceland’s climate and marine ecosystems.

Using these maps, it has been confirmed that calculating long-term trends in the ocean is difficult and unreliable. Excluding anthropogenic sources, there are many factors in play in determining bottom temperatures within the realm of Iceland’s continental shelf. Between the annual natural variation of ocean temperature and the presence of the subpolar gyres among a multitude of factors, there is an element of fogginess to AMOC measurement. More research into AMOC’s role in Iceland’s climate needs to be conducted to make more accurate future predictions.

One may think, isn’t global warming going to increase ocean temperatures not lower them? In general, the world’s oceans will increase in temperature. From 1995 to 2015, the ocean temperatures had been increasing, especially in the Southwest. According to article written by members of the Marine and Freshwater Institute, the waters off the Northeast coast of Iceland will see a significant increase in temperature in the future (Mason et al., 2021). Northeast Iceland receives cold, polar Arctic water but does not receive a freshwater flux like the Atlantic waters to the Southwest receive. As a result, this mixture of Arctic and Atlantic will likely see increases that reflect overall warming due to a rapid decrease of albedo from sea ice loss. Unlike the Greenland ice sheet, the sea ice is not freshwater, and so its effect will not be as profound.

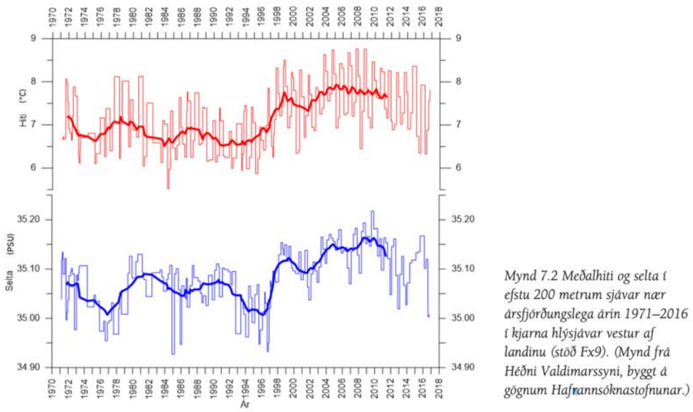


Figure 20: A graph of temperature and salinity measurements from a survey point located in the southwest of Iceland. Conducted by the Marine and Freshwater Institute, measurements of temperature in °C and salinity in PSU were taken quarterly over a 48-year record. The results indicate an overall increase in temperature but a small drop in temperature and salinity since 2010 (Iceland Meteorological Office, 2018).

<u>Bigger Picture Now</u>

No matter the level of weakening in the years to come, AMOC weakening in the North Atlantic demands the world's attention. Ecosystems are systems where everything relies on one another. If the populations of fish are changed drastically, all marine organisms will face potentially grave consequences in response to that change. Much like how the Gulf Stream current behaves, when a great regime shift occurs within the system, there is no going back; the damage is permanent. Isolated fish population collapses have occurred in the past due to climate-induced environmental patterns, but often the eradicated fish eventually return. But a worldwide, climate-driven *ecosystem* regime shift could easily cause irreparable damage in a short amount of time. Iceland could see a major re-shifting and potential collapse of marine ecosystems with strong AMOC weakening (Wilson, 2020).

For humans, changes in fish populations would not only be an economic issue but also a social, political, and cultural one. Most obviously, if cold-water or warm-water fish populations start to disappear from Icelandic waters, a serious economic toll could ensue. A political conflict over fishing rights (similar to the Iceland-Faroese Atlantic mackerel controversy) could rage if critical fish stocks migrated into disputed international waters or another country's EEZ in pursuit of suitable habitat conditions. Fishing companies could go bankrupt. Thousands of Icelandic fisherman and factory workers could lose their jobs. The price for fish in supermarkets could skyrocket. The government might have to invest in alternative dietary options to substitute for Icelandic fish. But inversely, if the RCP 8.5 and AMOC Shutdown scenarios actually do come true, important demersal fish like Atlantic cod could prosper. In conclusion, if cold-water fish that were previously dropping in numbers began thriving in Icelandic marine ecosystems again, Iceland could an experience an uptick in economic prosperity and increase of fishing quotas.

Within the Icelandic fishing industry, very few measures have been taken to prepare for the potential changes that very much could take place in a shorter time than scientists and politicians may realize. The most obvious "solution" to the problem of weakening Atlantic circulation is to reduce carbon emissions and to slow down the rate of freshwater flux into the North Atlantic.

Being a pretty unrealistic and overambitious short-term goal especially for a small island country like Iceland, it may be more important to focus on adaptation instead of mitigation. Iceland's government excels at enforcing fishing quotas and setting the TAC (total allowable catch) for every fish species at an adequate amount ("History of Fisheries". If the government studies the weakening of the Irminger Current and acknowledges the possibilities of both warmer and colder futures for Iceland, then solid fish recruitment over years could be make up for the environment-driven population migrations.

Conclusion

An AMOC weakening event could cause a unique negative feedback loop for Iceland, but overall the current circulation failure would have disastrous effects worldwide. Even in Iceland, who is considered to be a likely "climate change winner", permanent changes that will have permanent consequences for Iceland. A country with typically nutrient-rich waters, the lack of warm water in Iceland will create inhospitable conditions for many warm-water fish species and scramble the areas suitable for cold-water fish within Iceland's waters. If many of the fish populations in Iceland's EEZ collapse, negatives effects on the national economy and the local fishing communities could be profound.

In a phone call with the captain of the Jóna Eðvalds, a pelagic bottom trawl vessel working for Skinney-Þinganes, a large fishing company based in Höfn, the fisherman expressed a couple of concerns but seemed quite optimistic for the future. Since starting at Skinney in 2006, the captain has noticed that Atlantic mackerel in the southeast has started moving westward towards Norway. Another concern he explicitly expressed was that there was some instability in regard to the capelin fish stock in recent years. According to the MFRI, the capelin stock plummeted due to an overabundance of juvenile fish, but the stock has been well maintained by the government and could prosper in years to come. The captain did, however, seem quite content about the future in fishing, referencing the emergence of new pelagic species in Iceland's southern waters. Although the vessel specializes in catching pelagic fish and not demersal fish, the insight provides a reflection as to what Iceland fishermen think the future may hold with climate change becoming more prevalent (Danner, 2021).

With many "losers", there will be some "winners". Iceland, unlike much of the world, could experience an unusual cold climate unlike most all of the world's maritime countries. But with some pros there will likely be many cons. The currents around Iceland have weakened and will weaken until at least 2100. Sea level will continue to increase worldwide. A flood of climate refugees from severely affected countries could seek asylum in Iceland. The weakening or collapse of the ocean stability system could make North Atlantic marine ecosystems vulnerable to failure, and the ocean could experience rapid and extreme changes in nutrients and biodiversity. Even if climate change does "favor" Iceland, it will likely impact the country in ways that were previously unknown, making an unstable environment a new norm.

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