Problem Chosen	2020 MCM/ICM Summary Sheet	Team Control Number
A		2020105

Climate change can pose significant impacts on habitats of oceanic animals. Since rising sea water temperatures caused by global warming may affect fisheries along the coast of Scotland, we wish to model how fish population shifts might occur.

In this paper, we treat fish location at a given time as random variable and construct a time-varying Markov Chain model to estimate a probability distribution. Our model treats fish location as a function of temperature, which varies based on the oceanic sub-region chosen. We adopt a convention set by the Scottish government which divides legal Scottish fishing regions into 15 sub-regions, and treat each of the sub-regions as a "state" of our Markov chain. We then use computed transition probabilities to determine how likely it is that a fish will end up in a particular region after a fixed amount of time.

We use historic water temperature data to determine initial temperatures of the sub-regions and find that temperature data collected from 1997 to 2013 reflects a positive linear correlation between temperature change and time. We then use this data to update the transition probability matrix in the Markov chain at each iteration. We compute 50 iterations in the Markov chain with change in time $\Delta t = 1$ year.

In the best, worst, and average cases, fish in Scottish waters are predicted to be further north of the coastline by 2070. In the best case, when temperature increases by $0.01^o C$ per year, fish are predicted to be at least 100 km from northeastern shores and even further from more southern regions. Our results for an average or worst case, when temperature increases by $0.035^o C$ and $0.05^o C$ per year, respectively, are the same: fish will be far north of Scotland, at least 500 km from the coast, excluding ports off the mainland. Detailed prediction of the fish population location is presented numerically and graphically.

According to our model, the majority of the fish are expected to be found in sub-regions Balley, Faroe Shetland Channel, and Fladen after the year 2030, regardless of the rate of water temperature increase. Therefore, fishing companies not currently able to fish in these regions should consider managerial plans to relocate. This may involve moving current assets to ports further north, such as Lerwick, Stornoway, and Kirkwall. If fishing companies are unable to move, we recommend equipping current vessels with refrigeration.

Since we predict that fish populations will be most dense in the northernmost regions, our model also suggests that fish currently in Scottish waters might move into territorial waters of other countries, namely Denmark, Norway, and the rest of Scandinavia. Since regulations on international collaboration may become more stringent after Brexit, we encourage the Scottish fishing industry to enhance negotiation with neighboring countries to preemptively mitigate the economic impacts of moving fish populations.

A Random Walk Through the North Sea: Modeling the Effect of Climate Change on Scotland's Fisheries

2020105

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Hook Line and Sinker: The Impact of Climate Change on Scottish Fishing

Climate change stands to be one of the greatest threats that humanity faces in the 21^{st} century. Many of its ecological effects are well documented, including rising sea levels and frequent extreme weather events. However, as a modest Scottish fisherman, it may be easy to dismiss these predictions as just another news segment on television—*what does a hurricane in the Gulf of Mexico have to do with me?*

Quite a bit, as it turns out. Using historical Sea Surface Temperature (SST) data taken from the sea regions surrounding Scotland, our team built a probability model predicting Scottish herring mackerel migration in the next 50 years. The study predicts that in the best possible case—assuming an annual increase of 0.01° C—herring and mackerel may be up to $100km$ from the northeast ports of Scotland in 2070, and even further from ports in the south. In the worst case scenario, with an annual temperature increase of 0.05°C, the fish will move far to the north of Scotland: at least $500km$ from the coast.

If your fishing business currently relies on a large catch of herring and mackerel throughout the fishing season, you may need to start making strategic adjustments within the next couple of years. We recommend moving assets to the northern Scottish ports, including Lerwick, Stornoway, and Kirkwall, so that your boats can access the northern waters. If such a move is not possible for your business, we recommend equipping some of your boats with refrigeration capabilities to be able to make longer excursions towards the north, while retaining fish freshness.

In the case that your business is not able to make any of these changes, not all hope is lost. Our model also predicts that a small amount of herring and mackerel may remain near the southern ports during the warmer months. So, if you currently fish out of ports such as Cambeltown or Pittenweem, there is an advantage to staying put for now.

Whether you prepare or not, climate change is going to have a profound effect on the Scottish fishing industry. Following the recommendations above may allow your business to mitigate the negative consequences of rising ocean temperatures, but in any case, the Scottish people need to brace themselves for the economic impact that climate change will bring.

Introduction

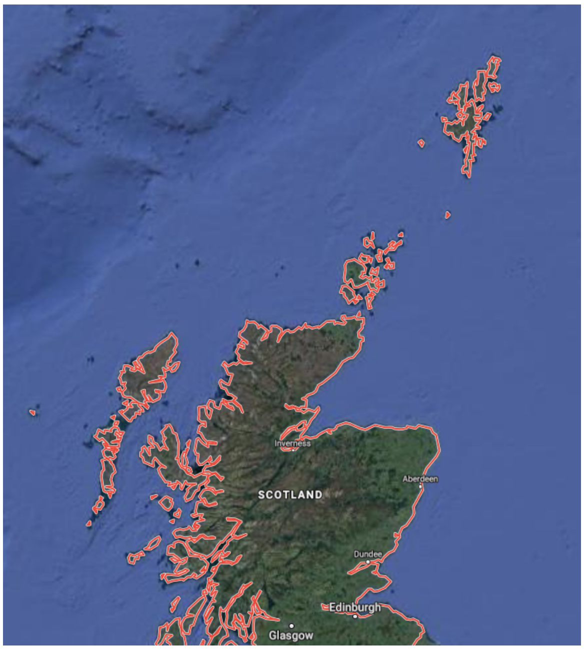


Figure 1: General map of ocean region around Scotland [15]

Climate change can pose significant impacts on habitats of oceanic animals. Located in the northernmost third of the United Kingdom, the landscape of Scotland contains a long distance of coastline, which provides ideal conditions for fishing. However, rising sea water temperatures caused by global warming may affect living habitants of Scottish waters. As the Scotland fishing industry is one of the biggest players in the UK fishing industry, contributing to two-thirds of the total fish caught in the country [17], this may be a cause for concern.

There are two commercial fish species in Scottish waters that the economy is highly dependent on: *herring* and *mackerel*. In this paper, we use a Markov chain model to predict how herring and mackerel will migrate as a response to water temperature increase in the next 50 years. Based on our predictive results, we will depict the best, the worst, and the most likely scenarios, corresponding to the least, the most, and the most probable amount of temperature change, of fish population density in 2070. Then, we will make suggestions to small fishing companies in Scotland to cope with the movement of fish habitats.

Temperature

Projections suggest that ocean temperatures around Scotland will increase overall in the next 50 years, specifically, temperatures in the North Sea region[5]. In this study, we focus on the *Sea Surface Temperature* (SST), because it is predicted that temperature change in deep waters will be very little [8] and the Scottish herring spawns in shallow coastal areas (15 - 45m depth) and the Atlantic mackerel lives close to the shore for most of the time in a year. For discussion in this paper, we refer to SST generally as "temperature".

By observing differences in decadal averages of temperature in the years 1982 - 1991 to 2009 - 2018, many models suggest that temperature will increase by 0.25 °C - 0.4 °C per decade [4]. Studies also have shown there may exist regional and seasonal differences in ocean temperature increase. It is projected that temperature of the ocean further south around the UK might rise more than the ocean in the north, and temperature increase in the fall is more dramatic than in the summer [8]. Climate-change impact studies also suggest that climate change will cause an increase in sea level and ocean acidification, and a decrease in salinity and primary production (autotrophs) in the North Sea region [5].

Geography

According to provisions of the United Nations Convention on the Law of the Sea (UNCLOS), the *Exclusive Economic Zones* (EEZ) is the seaward outermost boundary of 200 nautical miles from the low-water line [19]. The EEZ serves as the Scottish Fisheries Limits, which covers the North Sea and west of Scotland [10]. We adopt this convention to divide the Scottish Fishing Limits area into fifteen sea regions as in **Figure 2**. The fish we are concerned with lie in the pelagic zone, meaning they inhabit the water column, as opposed to the shore of bottom, of these regions[16].

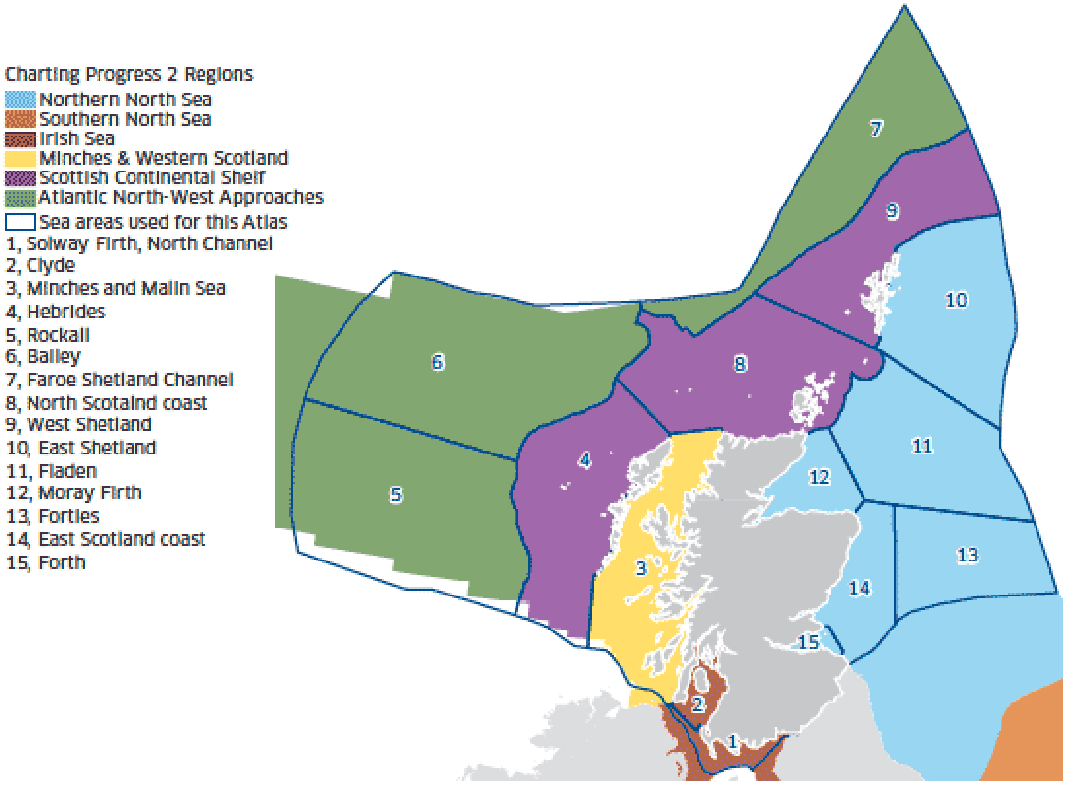


Figure 2: Map describing Scottish sea sub regions [11]

Herring

The term“herring” is used to categorize a number of species of fish, most of which are in the family *Clupeidae*. We take the term “Scottish Herring” to refer to Atlantic herring, *Clupea harengus*, the species most harvested in the Scotland and North Sea region and the only species of herring listed under *Marine and Fisheries* on the Scottish Government website [1]. It is thought that the diets of Atlantic herring are flexible, depending on season and *stock*, that is, a subpopulation of fish characterized by migration and feeding patterns. It is believed that there are multiple herring stocks around Scotland [1], displaying such differing behaviors that at least one population is spawning in a given month each year.[21]. When spawning, herring typically migrate from open water to more coastal waters[21]. Moreover, according to an article by *H. Gislason & T.H. Helgason*, studies suggest herring diet consists of varying amounts of copepods, sandeels, euphausids, Hyperia, and minimal amounts of fish larvae, cupeoids and gadoids[13]. Similarly, the stocks display different eating behaviors: in one study, 1% of the food in herring stomachs in the Northern North Sea region (refer to **Figure 2**) was composed of sandeels and fish larvae whereas it composed 9% for herring in the Shields area.

Mackerel

As with the term "herring", "mackerel" is a common name for a large subclass of fish. In this paper, we take "mackerel" to refer to the Atlantic mackerel, or *Scomber scombrus*. As of 2016, it is thought that there are two governing mackerel stocks in Scottish waters–the north and the western stock–which each migrate to shallow waters in the summer and back to deeper waters in winter, although to different locations[1]. They eat sprat, sandeels, gadoids, and Herring larvae[13]. They are also largely cannibalistic; in fact, in one study, the diet of juvenile mackerel 13-19 mm long was found to be 83% mackerel larvae[12].

Assumptions

As various copepods and other organisms which make up herring and mackerel diet are available throughout regions around Scotland, our model assumes availability of prey in all regions. Additionally, as mackerel are cannibalistic, the presence of some food is trivially present. However, autotroph production is thought to decrease overall in regions around the North Sea as climate changes[5], where a decrease in such production could effect the availability of all prey. We assume this decrease in production to be distributed evenly across the region. This assumption could affect overall population but assumes no effect on migratory behaviors; hence, it is not considered in our model.

Moreover, although mackerel tend to prey on herring larvae, since the mode of coexistence between mackerel and herring does not change with temperature increase, we omit predator-prey interactions for the simplicity of the model.

While we perform analysis on temperature data further in this paper, we treat surface temperature data as though the fish swim close to the surface. While this is consistent with findings–these fish are typically found up to 200 m from the surface [21] – our calculations do not consider this depth. The model also does not consider the effect of decreased salinity, or increased sea level and ocean acidification on fish movement.

Model

We wish to predict where fish will be in after a varying number of years given a starting location. To do so, we treat fish location at a given time as random variable, and construct a time-varying Markov chain model to estimate its probability distribution. We treat each of the 15 sub-regions of the sea surrounding Scotland as a "state" of our Markov chain, and use computed transition probabilities to determine how likely it is that a fish will end up in a particular region after a fixed amount of time.

Under the assumption that fish movement is determined entirely by changes in Sea Surface Temperature (SST), the transition probabilities in our model will be determined similarly, updated at each point in time to reflect changing ocean temperatures. Since fish migrate to spawn during different seasons, the time of year that we consider must be fixed to a particular month. We will consider a process in discrete time with change in time $\Delta t = 1$ year.

To build the Markov chain, we first need to estimate SST values for each of the sub-regions previously defined. Let $T_i(t)$ denote SST at a given region x_i at time t, where $t = 0, 1 \ldots, n_t$. We define $T_i(t)$ as

$$T_i(t) = T_i(t-1) + f_i(R)$$

where R is taken to be an estimate for annual temperature increase. Estimates of R vary [4] , and we use different values of R in our simulations to study best- and worst-case results. A discussion of the form of f_i is given below. We use initial temperature data for each sub-region (denoted $T_i(0)$) taken from "Monthly average sea surface temperature for 13 Scottish Sea Areas" published by the *Marine Scotland Open Data Network* [6] to begin the computation. The data [6] records monthly SST in the 15 sub-regions from 1997 to 2013. Hence, we use the 2013 data as the initial temperature inputs for our model.

Now, given a starting region x_i and a potential ending region x_j, we wish to compute the probability that a given fish will be in x_j after the elapsed time. Since we treat fish location as a function of SST, we can determine such a probability by comparing the temperature of the two regions in question to the temperature preferred by the species of fish. More specifically, we consider a function $c_{ij}(x_i, x_j)$ defined as:

$$c_{ij}(x_i, x_j) = \begin{cases} 0 & , \quad |\mathcal{O} - T_i| - |\mathcal{O} - T_j| \leq 0 \\ |\mathcal{O} - T_i| - |\mathcal{O} - T_j|, & \text{otherwise.} \end{cases}$$

where $\mathcal{O}$ denotes the average preferred temperature for herring and mackerel.

Moreover, we assume a fish can travel to a given region in an iteration only if the region in the previous iteration is adjacent to it. So, we let $M_{ij} = M(x_i, x_j)$ be defined as

$$M_{ij} = \begin{cases} 1, & x_i \text{ is adjacent to } x_j \\ 0, & \text{otherwise.} \end{cases}$$

We may now define $p_{ij} = p(x_i, x_j)$, the probability that a fish will travel from x_i to x_j:

$$p_{ij} = \frac{M_{ij}c_{ij}}{\sum_{k=0}^{15} M_{ik}c_{ik}}.$$

Finally, we use these probabilities p_{ij} to construct our transition probability matrix P. At each iteration, we have a matrix-vector product:

$$\boldsymbol{\rho}_{t+1} = P\boldsymbol{\rho}_t = \begin{pmatrix} p_{11} & \cdots & p_{1,15} \\ \vdots & \ddots & \vdots \\ p_{15,1} & \cdots & p_{15,15} \end{pmatrix} \begin{pmatrix} \rho_{t,1} \\ \vdots \\ \rho_{t,n} \end{pmatrix}$$

where $\boldsymbol{\rho}_t$ represents the probability distribution of the fish's location at the current time t. Each entry $\rho_{t,i}$ is the probability that a fish will be at location x_i at time $t+1$ given its starting location.

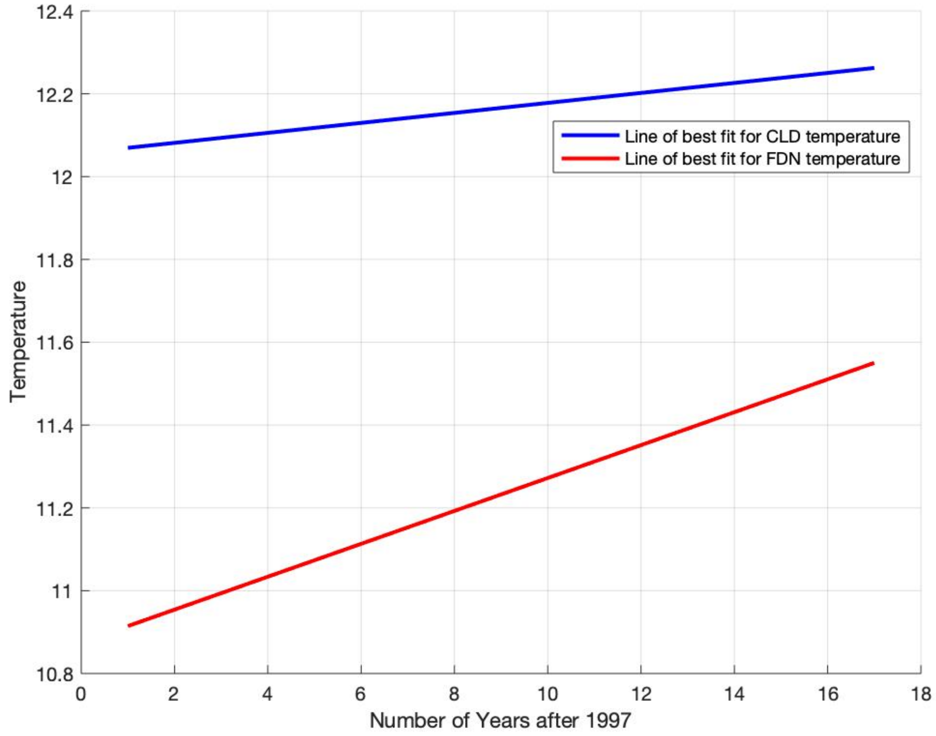
We then update the temperatures T_i, and we compute another iteration as described above. After repeating this process n_t times, the final probability vector $\boldsymbol{\rho}_{n_t}$ indicates our estimate of the probability distribution for the location of the fish after the full length of time has elapsed.

Analysis

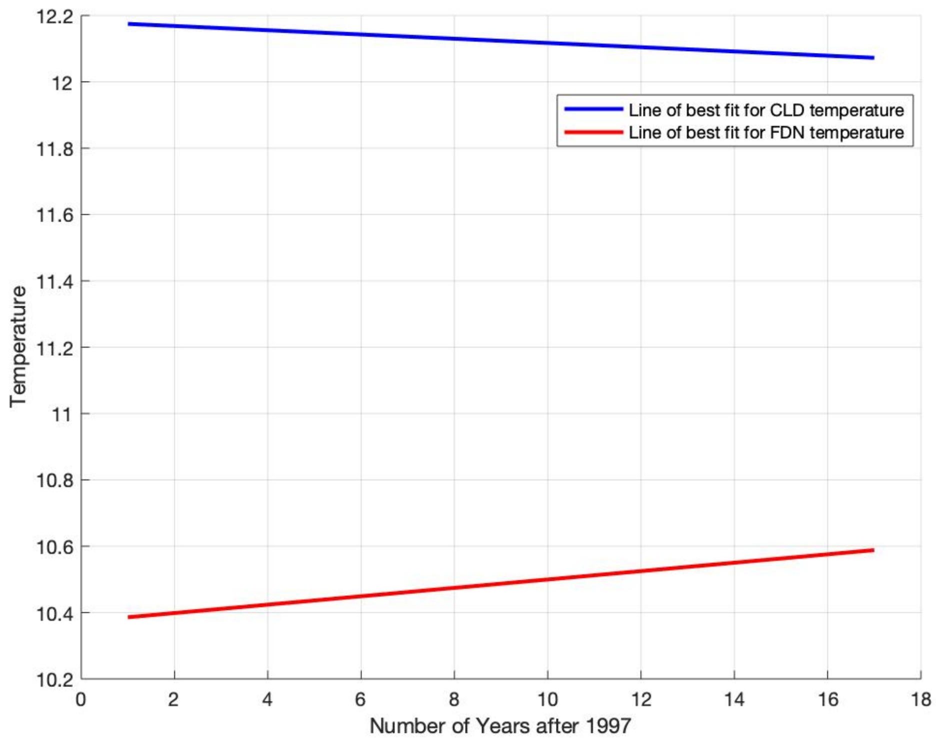
Temperature Increase (Determining the T_i's)

We might incorporate latitudinal information corresponding to each sub-region in our function f_i. One study found that the SST in the southernmost sub-regions can increase up to 0.025^o C more than regions in the north annually [8]. However, before we have a form for the f_i, we must first consider how temperature increases.

Many past studies suggest that Scottish sea temperature will rise at an average rate of between 0.2°C to 0.5 °C per decade until the end of 21st century [11]. We examine historic data of temperature to verify such a rate of temperature increase. Using the data presented in "Monthly average sea surface temperature for 13 Scottish Sea Areas" [6], we select two sea regions as samples, Clyde (CLD) and Fladen (FDN), each on the east and west coast of Scotland, respectively, and create a data visualization of the patterns of temperature change from 1997 to 2013.



Temperature vs. Year, June 1997-2013



Temperature vs. Year, November 1997-2013

After fitting the data to polynomials of different degrees, we found that the degree one polynomial gives the smallest error. The rate of temperature change given by the coefficient of the linear approximation ranges from 0.012 °C per year to 0.04 °C per year, which is consistent with the average temperature increase rate indicated in previous studies. This result leads us to our formulation of the function $f_i(R)$:

Let $\tau_i \in [0, 0.025]$ account for the latitude of each sub-region, where $\tau_i > \tau_j$ if x_i's southern border is south of x_i's southern border. The exact values of the τ_i are defined below:

τ_1 0.025	τ_2 0.023214	τ_3 0.019643	τ_4 0.0125	τ_5 0.014286
τ_6 0.007143	τ_7 0	τ_8 0.005357	τ_9 0.001786	τ_{10} 0.003571
τ_{11} 0.008929	τ_{12} 0.010714	τ_{13} 0.016071	τ_{14} 0.017857	τ_{15} 0.021429

Then, we define f_i as

$$f_i(R) = R + \tau_i,$$

where R is the chosen temperature value to increment by in each iteration. In our simulation, we use $R = 0.01, 0.035, 0.05$ as our annual temperature increase coefficients to study a best-case, most-likely, and worst-case scenario of warming ocean temperatures.

Finally, for all simulations, we use an optimal temperature of 12° C, chosen as the average preferred temperature of both fish, consistent with previous findings[2, 20], yielding the following form for the c_{ij}'s:

$$c_{ij}(x_i, x_j) = \begin{cases} 0 & , \quad |12 - T_i| - |12 - T_j| \leq 0 \\ |12 - T_i| - |12 - T_j|, & \text{otherwise.} \end{cases}$$

where each $T_i(t)$, $i = 1, \ldots, 15$ is defined as:

$$T_i(t) = T_i(t-1) + R + \tau_i.$$

Simulation Data

Using the Markov chain model described, we ran numerical simulations to estimate the probability distribution of the location of an arbitrary fish after a set period of time. We chose April and October as months for simulation. As SST is less variable during the Summer and Winter months, and so choosing months in the Spring and Fall allowed us to more realistically study the effects of rising temperature.

The simulations were conducted as follows. After fixing the optimal temperature $\mathcal{O}$, a month of the year (April or October), and a temperature increment value R, we generated probability vectors $\hat{\boldsymbol{\rho}}_5, \hat{\boldsymbol{\rho}}_{10}, \hat{\boldsymbol{\rho}}_{25}$, and $\hat{\boldsymbol{\rho}}_{50}$ in MATLAB, corresponding to the probability distribution of fish location after 5, 10, 25, and 50 years respectively. Note that the vectors $\boldsymbol{\rho}_t$ described above correspond to conditional probability vectors, conditioned on the fish's starting location. However, each $\hat{\boldsymbol{\rho}}_t$ is a vector of marginal probabilities. To compute $\hat{\boldsymbol{\rho}}_t$, we ran a simulation under the fixed conditions with each region as a starting point, and used these resulting $\boldsymbol{\rho}_t$ vectors to compute the desired marginal probabilities (we assume that a fish is equally likely to start in each region). More explicitly, we have

$$\hat{\rho}_{t,i} = \frac{1}{15}\sum_{j=1}^{15} \rho_{t,i,j}$$

where $\rho_{t,i,j}$ is the probability that a fish will end up in Region i at time $t+1$, given that they started in Region j.

The resulting probability vectors for each combination of month and R value are shown in the six tables below.

April, R=0.01

Region	2025	2030	2045	2070
1	0.06667	0.06667	0.06667	0.06667
2	0	0	0	0
3	0	0	0	0
4	0.00087	0	0	0
5	0.61198	0.61667	0.61667	0.61667
6	0.00374	0	0	0
7	0.00008	0	0	0
8	0	0	0	0
9	0.24655	0.24655	0.24655	0.24655
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0.07011	0.07011	0.07011	0.07011

October, R=0.01

Region	2025	2030	2045	2070
1	0.00000	0.00000	0.00000	0.00000
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0.0001	0	0	0
6	0.00673	0.68303	0.68303	0.68303
7	0	0	0	0
8	0.6762	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0	0.31697	0.31697	0.31697
12	0	0	0	0
13	0	0	0	0
14	0.31693	0	0	0
15	0.00003	0	0	0

April, R=0.035

Region	2025	2030	2045	2070
1	0.06667	0.06667	0.06667	0.06667
2	0	0	0	0
3	0	0	0	0
4	0.00087	0	0	0
5	0.61198	0.61667	0.61667	0
6	0.00374	0	0	0.61667
7	0.00008	0	0	0
8	0	0	0	0
9	0.24655	0.24655	0.24655	0.24655
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0.07011	0.07011	0.07011	0.07011

October, R=0.035

Region	2025	2030	2045	2070
1	0.00000	0.00000	0.00000	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0.00006	0	0	0
6	0.00869	0.68882	0.68882	0
7	0	0	0	1
8	0.67571	0	0	0
9	0	0	0	0
10	0	0	0	0
11	0.04791	0.31118	0.31118	0
12	0	0	0	0
13	0.26762	0	0	0
14	0	0	0	0
15	0	0	0	0

April, R=0.05

Region	2025	2030	2045	2070
1	0.06667	0.06667	0.06667	0.06667
2	0	0	0	0
3	0	0	0	0
4	0.00087	0	0	0
5	0.61198	0.61667	0.61667	0
6	0.00374	0	0	0.61667
7	0.00008	0	0	0
8	0	0	0	0
9	0.24655	0.24655	0.24655	0.24655
10	0	0	0	0
11	0	0	0	0
12	0	0	0	0
13	0	0	0	0
14	0	0	0	0
15	0.07011	0.07011	0.07011	0.07011

October, R=0.05

Region	2025	2030	2045	2070
1	0	0	0	0
2	0	0	0	0
3	0	0	0	0
4	0	0	0	0
5	0.00006	0	0	0
6	0.01014	0.68642	0	0
7	0	0	0	1
8	0.67623	0	0	0
9	0	0	1	0
10	0	0	0	0
11	0.00082	0.31358	0	0
12	0	0	0	0
13	0.31275	0	0	0
14	0	0	0	0
15	0	0	0	0

Results

General Trends

For all choices of month, rate of temperature increase, and number of iterations, our model suggests that fish will move northward. For choice $n_t = 5$ (2025), between both months proportions of fish are found in just about all sub-regions, with the highest populations estimated to be in areas 5, 8, 9, 13, and 14 (see **Figure 3** below). Populations become more dense but are found in fewer areas of Scottish waters after another 5 years (2030), with the highest populations predicted to be in areas 5, 6, 9, and 11. Population densities are maintained when computed after another 15 years (2045) except for October, $R = 0.05$, where the algorithm predicts fish will move from sub-regions 6 and 11 to sub-region 9 between 2030 and 2045. Finally, choice $n_t = 50$ (2070) is fairly consistent with predictions from previous years, with slight modification, described in more detail below.

In total, the results appear to be more sparse after fewer iterations. This might be caused, in part, by our restriction to movement to neighboring sub-regions. Additionally, many of the predictions appear to stay consistent across time. Finally, it appears that the October data is more sensitive to changes in R, which may be because October starting temperatures are more variable across the regions.

Fifty Years From Now

April data suggests that, in the year 2070, for all choices of R population density of fish will be highest in sub-region 6, with about 62% of fish residing there, and second-highest in sub-region 9 with 25%. October data suggests that in the year 2070, for choice $R = 0.01$, population density of fish will also be highest in sub-region 6, with about 68% of fish residing there, and second-highest in sub-region 11 with about 32%; choices

$R = 0.035$ and $R = 0.05$ estimate that all fish will be in sub-region 7. Together, these are the regions located furthest north. Hence, by 2070, the most probable destinations for the fish after 50 years are Regions 6,7, 9, and 11, as displayed in **Figure 3**. Notably, this is consistent with the 10-year predictions.

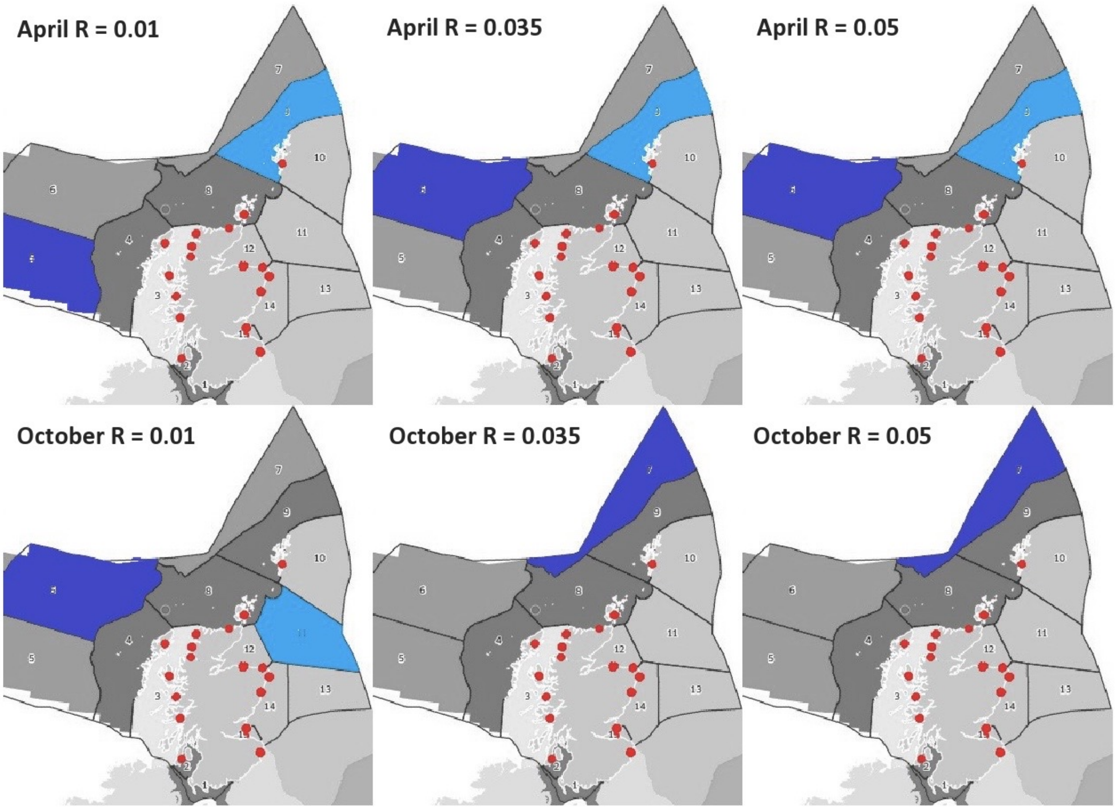


Figure 3: Schematic of population density predictions based on government-defined oceanic subregions. **Key:** dark blue = > 55% population density; light blue = < 50% but > 10% population density, gray = < 10% population density.

Best, Worst, Average Case

In all three cases, fish in Scottish waters are predicted to be fairly far north of the coastline. In the best case, $R = 0.01$, fish are predicted to be at least 100 km from northeast regions and even further from more southern regions. Meanwhile, our results for an average or worst case, $R = 0.035, 0.05$, are the same: fish will be found further north, at least 500 km from the coast, excluding ports off the mainland, such as Lerwick.[1] In these cases, since the regions fish population is most dense are the furthest north regions, this might also suggest that fish will move out of Scottish waters and into international or other territorial waters.

[1]We calculated these distances with the map software *Cadcorp*. The software allowed us to select two points on a map and calculate its Euclidean distance.

Suggestions

In order to make business predictions based on capabilities of small-scale fishing companies, we must first define what it means to be small-scale and compound data about where these fisheries are located. The European Commission defines a small-scale coastal fleet to be a vessel less than 12 meters in length[3]. While some sources claim that boat length as a metric for "small-scale" is too narrow and may interfere with EU policies[9], for our purposes, we will be looking strictly at vessel length.

According to previous surveys, on average, a small fishing vessel with length less than 12 m travels about 17.31 hours from its home port to the fishing ground, and the average distance between the port and the fishing ground is about 51 km [7]. Currently, most small-scale vessels owned by small companies lack sufficient refrigeration equipment [3]. Therefore, we predict that small fishing vessels would not be able to transport their landings from fishing grounds further than 51 km from the coast back to the land within one day. The map on the right (**Figure 4**) from the *Maritime Boundaries Geodatabase* [14] shows the Contiguous Zones of Scotland, which is defined to be 24 nautical miles ($\approx$ 45 km) seaward from the coastline. We use the Contiguous Zones to display the average reach of a small-scale fishing vessel with home port on the coast of Scotland.

Figure 4: Contiguous Zones (24 Nautical Miles $\approx$ 45 km of Scotland [14]

At the beginning of 2020, the UK released data concerning fishing vessels and locations of 10 m of length and under that assigns the number of fishing vessels to each administrative port[2] as of January 1, 2020[18]. We restricted the data we used to those ports located in Scotland and compiled the data into **Figure 5** below.

According to our model, the majority of the fish will be found in Regions 6, 7, and 11 after the year 2030, regardless of the rate of increase in SST. Therefore, any fishing companies which are not currently able to fish in these regions should begin taking necessary steps to do so. This may involve moving their current assets to ports closer to the north—in particular, the ports Lerwick, Stornoway, and Kirkwall seem to offer the most optimal positions. If fishing companies are unable to move to these island ports, it may be more beneficial to equip their current vessels with refrigeration so that they can return fresh fish from the further regions back to Scotland.

[2]Here, we treat administrative port as the home port of the vessel based on the availability of the data.

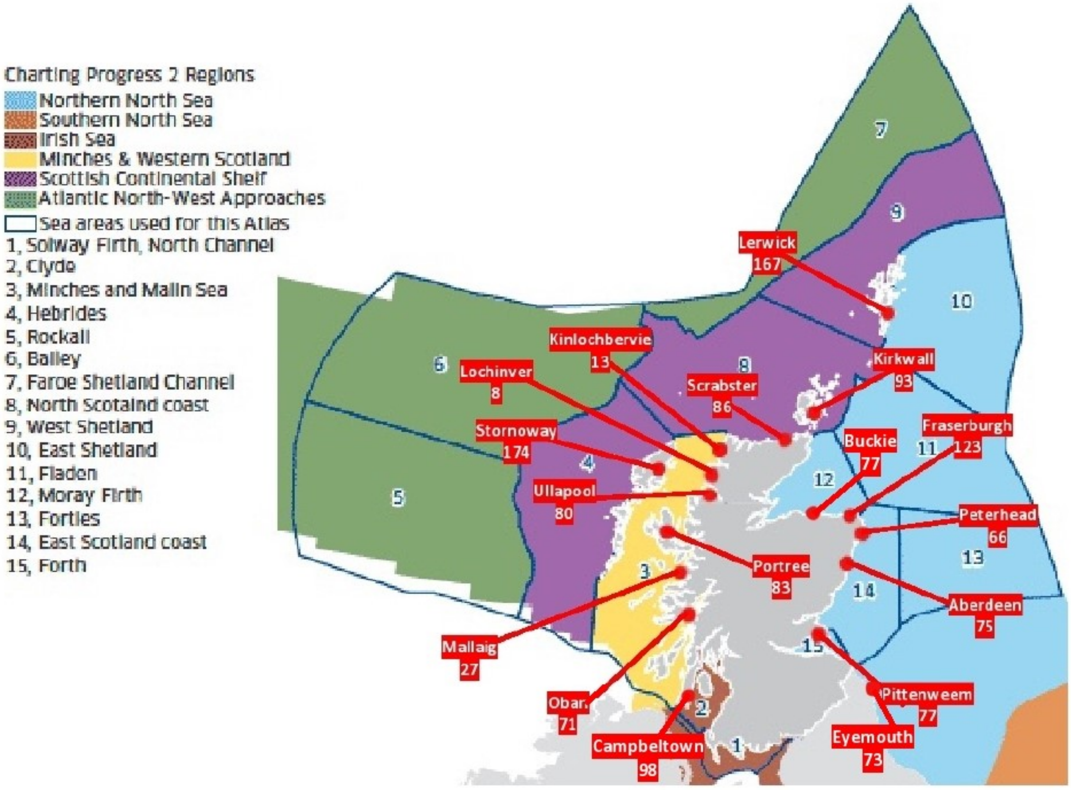


Figure 5: Number of small-scale fishing vessels registered at Scottish ports[11].

Regarding Territorial Waters

Since our model is defined using the current sea regions of Scotland, we cannot directly predict whether the fish will enter international or territorial waters of any other country. However, it is clear that the movement of fish is trending towards the north. Scotland may need to negotiate with other countries that fish near the Atlantic North-West, Scottish Continental Shelf, and Northern North Sea, such as Denmark, Norway, and the rest of Scandinavia, for the right to fish further north. Otherwise, Scotland may need to position itself economically to withstand this blow to its fishing industry. Since regulations on international collaboration may become more stringent after Brexit, we encourage the Scottish fishing industry to enhance negotiation with neighboring countries which would face similar difficulties in the near future. Some valuable motions may include establishing multi-nationally owned ports on northern islands or forming international organizations to rent or distribute refrigerated vessels to small fishing companies to meet individualized demand.

It is also useful to note the effect that climate change may have on Scotland's territorial waters. As sea levels rise, Scotland's coast will be pushed further inland, and since the territorial waters are defined as the sea within 200 nautical miles of a country's coastline, Scotland's territorial waters may be pushed further south. This will only make fishing to the north more difficult.

Limitations

Some of the limitations of our model may come as a result of the assumptions that we make regarding Scotland's geography and fish behavior. By treating the ocean surrounding Scotland as a network of sea regions, we may lose the ability to be specific with our location predictions. Additionally, since we treat the sea around Scotland as a fixed network, we are unable to predict whether or not the fish will leave Scottish waters entirely. For example, even though we predict that the fish will migrate to the northernmost regions, it is possible that an area even further to the north provides a more optimal temperature for the fish. Our model fails to identify populations, although it is able to identify proportions of these populations; the starting conditions assume that there is an equal chance a given fish will be found in any region.

Additionally, the increasing temperature may affect the organisms that herring and mackerel feed on. The model assumes that spawning and feeding habits of fish stay constant over time, while these dynamics may have effects not considered in our model.

Finally, since our model only predicts the annual temperature in each region for a fixed month, we fail to incorporate the change in temperature that can occur throughout the year and the effect that this may have on migration. We might recommend replicating our study with data for all twelve months. Additionally, since the fish migrate periodically throughout the year, considering only one month at a time may allow our predictions to be more accurate.

Conclusion

Climate change will cause ocean temperatures to increase all over the world over the next 50 years. In particular, these rising temperatures will cause sea surface temperatures to rise around Scotland, which may affect the migration habits of the herring and mackerel that live there. Using a time-varying Markov chain model, we predict that herring and mackerel populations around Scotland will be forced to migrate further north to escape rising temperatures in the south, even in the best-case scenario.

The decision to use a stochastic rather than deterministic model requires discussion. The Markov chain model allows us to represent "space" (i.e., the sea surrounding Scotland) efficiently, providing a precise language with which we could the express the movement of fish. Running simulations with our model is very computationally efficient, which allowed us to try several combinations of initial conditions (month, R) without too much computational overhead. The results of the Markov chain simulation are highly interpretable, and easy to explain to an audience of fishermen.

This migration will almost certainly impact the Scottish fishing industry. Small fishing companies that currently operate out of the southern ports will need to move their assets to the north to catch these fish. Any fishing companies that don't have the means to do so should consider improving the quality of their fishing boats, primarily by add refrigeration in order to return fresh fish back to Scotland. The Scottish government should prepare for the economic impact of this fish migration, potentially by negotiating with nearby countries for expanded fishing rights.

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