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**2020**
**MCM/ICM**
**Summary Sheet**

# When "Spring" Comes to North Atlantic


**Summary**

Atlantic mackerel and herring are two major species among Scotland's abundant fishery resources. However, as the negative effect of global warming is consistently threatening their habitats near Scotland, they may migrate to other waters in response to the change in sea temperature.

To predict their potential migration and evaluate the consequent impact to small fishing companies in Scotland, the Scottish North Atlantic Fishery Management Consortium hired us to establish mathematical models as a tool to identify the most likely habitats of these two species over the next 50 years, and give pragmatic suggestions to these small fishing companies to improve their operation strategy.

As a result, we first decomposed the big task into two smaller subproblems, and then developed three mathematical models to solve the subproblems stage by stage.

The first model, Sea Temperature Model (STM), is utilized to estimate sea temperature near Scotland over the next 50 years. We collected three real world data sets, and observed sea temperature has both warming trend and seasonality. To maintain these two characteristics, we implemented time series analysis by Holt-Winters' seasonal forecasting method, and visualized the estimated data by heatmaps.

The second model, Migration Model (MM), implements Markov process to simulate the future habitats of Atlantic mackerel and herring. We used sea temperature data obtained by STM to perform simulation, and discovered that Atlantic mackerel and herring are moving North as sea temperature changes over the next 50 years.

The third model, Fishery Profit Model (FPM), analyzes the shortest (3 years), longest (45 years), and average (18.79 years) elapsed time until small Scottish fishing companies could no longer benefit from current operation. Also, we performed cost-benefit analysis and put forward three suggestions to these small fishing companies, namely, shifting to larger vessels, fishing in high seas, and relocating assets to Northern regions such as Iceland.



**Keywords**:
Time Series Analysis, Markov Process, Cost-Benefit Analysis, Probabilistic Simulation, Data Visualization

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# 1 Introduction

## 1.1 Background

Atlantic mackerel and herring are two major species among Scotland's abundant fishery resources. According to the Scottish government's statistics in 2018, they were also fishes with the most considerable profits: mackerel with £164 million, and herring with £24 million [1]. However, as the consequence of global warming is consistently threatening the habitats of mackerel and herring near Scotland, they may migrate to other waters in response to the change in sea temperature. Because a large number of small fishing companies in Scotland are highly dependent on these two fish species, therefore, to predict the potential migration of Atlantic mackerel and herring becomes an essential topic to the survival of these Scottish small fishing companies since only by solid predictive analysis can we put forward pragmatic suggestions for their future operation strategies.

## 1.2 A Glance at the Data Sets

In order to formulate a well-founded and convincing report, we collected comprehensive data sets including key information such as sea temperature, fish distribution, and parameters of different fishing vessels. Here are the data sets that we utilized to establish our models,

- **Hadley Centre Sea Ice and Sea Surface Temperature Data Set (HadISST)**, a unique combination of monthly globally-complete fields of sea surface temperature and sea ice concentration on a 1 degree latitude-longitude grid from 1870 to date [2].
- **Global Historical Climatology Network-Monthly (GHCN-M)**, an integrated data set of climate summaries from land surface stations across the globe [3].
- **Climate Change: Earth Surface Temperature Data (EST)**, obtained by 1.6 billion temperature reports from 16 pre-existing archives [4].
- **International Mackerel Egg Surveys in the North Sea 2002–2011 & Western Areas 1977–2007 Data Set (ICES-WGMEGS)**, an experimental database that reflects the population and habitats of Atlantic mackerel near Scotland [5]-[7].
- **Scottish Sea Fisheries Statistics 2018 (SSFS)**, annual fishery data collected by the Scottish government [1].
- **Technical, Operational & Economic Characteristics of Selected Fishing Vessels Data (SFVD)**, a multi-aspect data set containing various features of selected fishing vessels from different countries [8].

We clustered these data sets into two categories, one for developing our predictions and suggestions, the other for validation and sensitivity evaluation. Further, we visualized fifty-year temperature and fishery data from a geographical perspective, making it more intuitionistic for readers to understand the potential migration of Atlantic mackerel and herring as sea temperature changes.

## 2 Problem Analysis and Decomposition

By careful study, we decided to first implement the idea of problem decomposition to simplify the task from the Scottish North Atlantic Fishery Management Consortium mainly into two smaller subproblems, and then find their solutions stage by stage. The two subproblems are,

**Subproblem 1.** *Determine the change of sea temperature near Scotland over the next 50 years, and identify new annual distribution of Atlantic mackerel and herring based on simulation results.*

It is necessary to solve Subproblem 1 by the following procedure,

- Step 1: Choose a sea temperature data set from HadISST, GHCN-M, or EST as benchmark, predict future change of sea temperature by time series analysis based on past data.
- Step 2: Validate the sea temperature change model by data not selected in Step 1.
- Step 3: Establish a probabilistic model to simulate the migration process of Atlantic mackerel and herring using ICES-WGMEGS and SSFS data.

Based on the results from Subproblem 1, Subproblem 2 asks us to,

**Subproblem 2.** *Build an economic model to analyze the costs and benefits of small fishing companies' operation and find strategies for them to improve their profits.*

It is necessary to solve Subproblem 2 by the following procedure,

- Step 1: Utilize SSFS and SFVD data to locate the fishing area that is reachable for small fishing companies.
- Step 2: Simulate the operation of small fishing companies and perform cost–benefit analysis to calculate their net profits.
- Step 3: Repeat simulation multiple times, and determine ① the worst case (shortest elapsed time), ② the best case (longest elapsed time), and ③ the most likely case (average elapsed time) until small fishing companies are no longer able to make profits.
- Step 4: Implement different operation strategies such as relocating assets and using vessels without land-based support to improve profits for small fishing companies.
- Step 5: Evaluate the economic impact if some Atlantic mackerel and herring pupolation moves into the territorial waters of another country.

For better understanding of how different steps are connected with each other to form the final solution, we can visualize the procedure of solving both subproblems by the flowchart on next page.

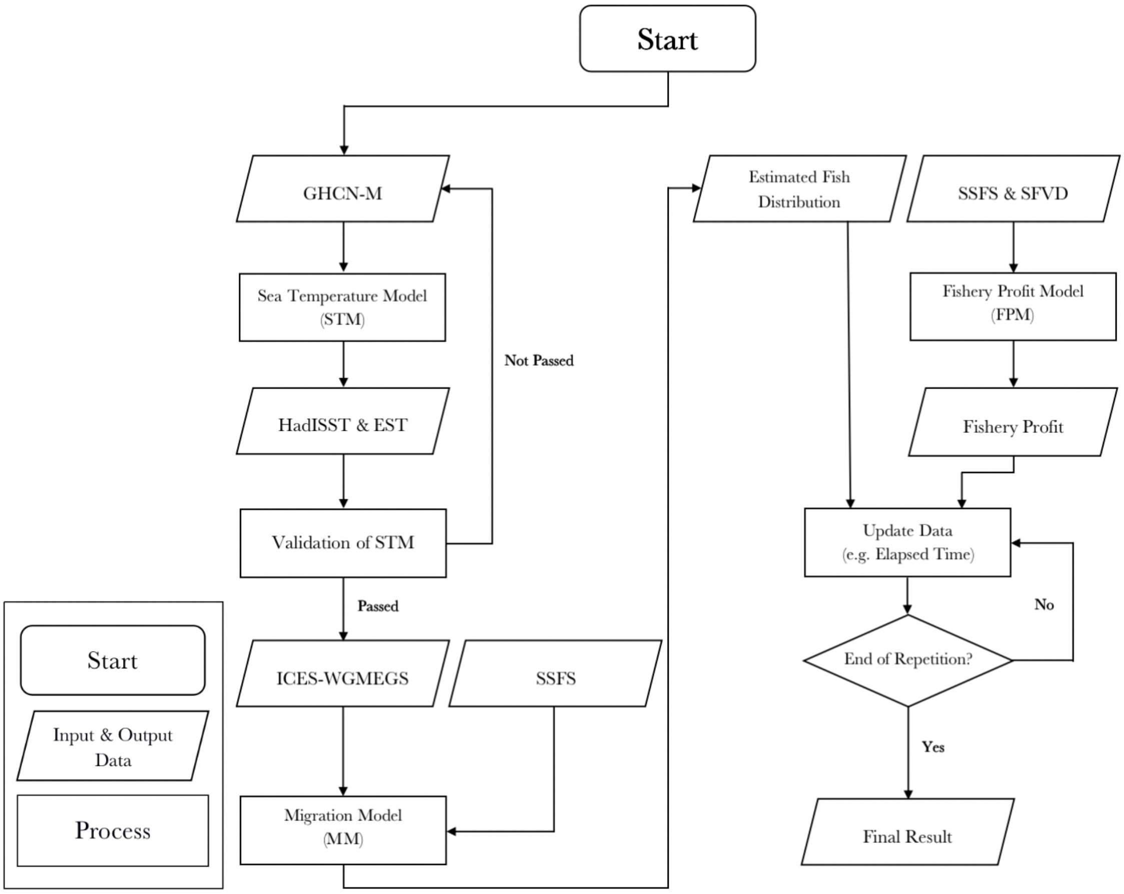



Figure 1. Modeling Workflow

# 3 Assumptions

- **Assumption 1: Atlantic mackerel and herring have the same habitats near Scotland**, since according to recent surveys, these two species have similar preference for environmental variables and habitat features [9].
- **Assumption 2: The only factor that drives Atlantic mackerel and herring to migrate is sea temperature**, we ignore other factors (e.g. ocean currents) that may cause their potential migration.
- **Assumption 3: The total fish population maintains current level over the next 50 years**, because we assume that high reproduction rate can compensate for the loss of population caught by humans.
- **Assumption 4: Without change of operation strategy, the Scottish small fishing companies' fishing ground is the entire UK's Exclusive Economic Zone (EEZ)** [1] , under the assumption that these small fishing companies are all capable of reaching the border of UK's EEZ.

[1]An Exclusive Economic Zone (EEZ) is a sea zone over which a state has special rights regarding the exploration and use of marine resources [10].

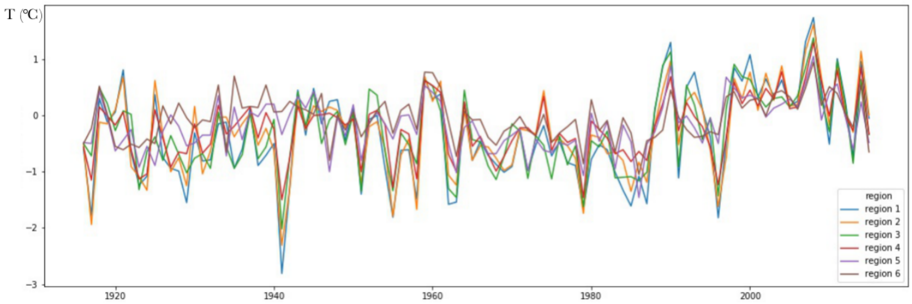
## 4 Notations

| Symbol | Definition | Model | Unit |
|---|---|---|---|
| $T_t$ | the sea temperature observed in year $t$ | all three | °C |
| $S_t$ | the smoothed sea temperature in year $t$ | STM | °C |
| $P_{t+m}$ | the predicted sea temperature at $m$ periods ahead year $t$ | STM | °C |
| $A_i$ | the average sea temperature observed in season $i$ | STM | °C |
| $b$ | the trend factor | STM | °C |
| $I$ | the seasonal index | STM | |
| $T_i(t)$ | the temperature of the $i^{th}$ grid in year $t$ | MM | °C |
| $N_i(t)$ | the amount of fishes in the $i^{th}$ grid in year $t$ | MM | Tonnage |
| $D_i(t)$ | the fish density in the $i^{th}$ grid in year $t$ | MM | Tonnage |
| $r_{ij}$ | the incoming rate from grid $j$ to grid $i$ | MM | |
| $J_{ij}$ | the migration flow from grid $j$ to grid $i$ | MM | Tonnage |
| $p_{ij}$ | the migration probability from grid $j$ to grid $i$ | MM | |
| $FC_{i,j}$ | the fuel costs for vessel $i$ at location $j$ | FPM | $ |
| $C_{i,j}$ | the fuel consumption rate of vessel $i$ at location $j$ | FPM | $sec^{-1}$ |
| $SFC_i$ | the specific fuel consumption of vessel $i$ | FPM | $g/kwh$ |
| $LF$ | the load factor | FPM | |
| $LC_i$ | the labor costs for vessel $i$ | FPM | $ |
| $TotalRev$ | the total revenue | FPM | $ |

# 5 Sea Temperature Model (STM)

## 5.1 Predicting Data with Trend and Seasonality

To estimate sea temperature over the next 50 years, a fundamental essential is to form an insight into the past data, becasue only with meticulous observation can we discover its key characteristics and choose an appropriate method for prediction. Therefore, we utilized GHCN-M data set and plotted sea temperature in six different maritime spaces near Scotland between 1880 and 2016.




| Region | Longitude | Latitude |
|---|---|---|
| 1 | $10^\circ - 15^\circ$ W | $55^\circ - 60^\circ$ N |
| 2 | $15^\circ - 20^\circ$ W | $55^\circ - 60^\circ$ N |
| 3 | $20^\circ - 25^\circ$ W | $55^\circ - 60^\circ$ N |
| 4 | $10^\circ - 15^\circ$ W | $50^\circ - 55^\circ$ N |
| 5 | $15^\circ - 20^\circ$ W | $50^\circ - 55^\circ$ N |
| 6 | $20^\circ - 25^\circ$ W | $50^\circ - 55^\circ$ N |

Figure 2. Change in Sea Temperature near Scotland between 1880 and 2016

From the diagram above, we summarized two important findings,

- **First, sea temperature near Scotland has a warming trend**, which further substantiates the theory that global warming is heating the Northeast Atlantic.
- **Second, sea temperature near Scotland fluctuated periodically during the past 100 years**, which is reflected by oscillations in the diagram.

In conclusion, sea temperature near Scotland has seasonality and is warming continuously, we must develop a model that is capable of handling data with both trend and seasonality. As a result, an exponential smoothing strategy that is widely used in time series analysis, Holt-Winters' seasonal forecasting method, becomes the best choice.

## 5.2 Time Series Analysis by Holt-Winters' Seasonal Forecasting Method

Holt-Winters' seasonal forecasting method was originally invented to forecast trends in production, inventories, and labor force [11]. It is also known as triple exponential smoothing method as it includes three smoothing equations in prediction to calculate overall result, trend, and also seasonality. Our implementation of Holt-Winters in STM is explained as follows,

$$S_t = \alpha \frac{T_t}{I_{t-n}} + (1-\alpha)(S_{t-1} + b_{t-1}) \qquad \text{(Overall Smoothing)}$$

Where $T_t$ is the sea temperature observed in year $t$, $S_t$ is the smoothed sea temperature in year $t$, $n$ is the number of periods in a season, $b$ is the trend factor, $I$ is the seasonal index, $\alpha$ is a constant.

After calculating $S_t$, update $b$ and $I$ by,

$$b_t = \beta(S_t - S_{t-1}) + (1-\beta)b_{t-1} \qquad \text{(Trend Smoothing)}$$

$$I_t = \gamma\frac{T_t}{St} + (1-\beta)I_{t-n} \qquad \text{(Seasonal Smoothing)}$$

Where $\beta$ and $\gamma$ are constants.

Finally, $P_{t+m}$, the predicted sea temperature at $m$ periods ahead is obtained by,

$$P_{t+m} = (S_t + mb_t)I_{t-n+m} \qquad \text{(Prediction)}$$

We set 30 years as a complete season, and set $n$ as 6, such that one period contains 5 years. From 1880 to 2016, 4 seasons can be used to predict future sea temperature.

For simulation, we chose the first two complete seasons to initialize b,

$$b = \frac{1}{6}(\frac{T_{30+5+1880} - T_{5+1880}}{6} + \frac{T_{30+10+1880} - T_{10+1880}}{6} + ... + \frac{T_{30+30+1880} - T_{30+1880}}{6})$$
$$= \frac{1}{6}(\frac{T_{1915} - T_{1885}}{6} + \frac{T_{1920} - T_{1890}}{6} + ... + \frac{T_{1940} - T_{1910}}{6})$$

As for the initialization of $I$, we calculated the average seasonal sea temperature, $A$, then divided the observed data by this average.

| Season 1 | Season 2 | Season 3 | Season 4 |
|---|---|---|---|
| $T_{1885}/A_1$ | $T_{1915}/A_2$ | $T_{1945}/A_3$ | $T_{1975}/A_3$ |
| $T_{1890}/A_1$ | $T_{1920}/A_2$ | $T_{1950}/A_3$ | $T_{1980}/A_3$ |
| ... | ... | ... | ... |
| $T_{1910}/A_1$ | $T_{1940}/A_2$ | $T_{1970}/A_3$ | $T_{2000}/A_3$ |

Where $A_i = \Sigma T_j/n$ (for $T_j$ in Season $j$).

Then seasonal indices are initialized by averaging each row,

$$I_1 = (T_{1885}/A_1 + T_{1915}/A_2 + T_{1945}/A_3 + T_{1975}/A_3)/4$$

$$I_2 = (T_{1890}/A_1 + T_{1920}/A_2 + T_{1950}/A_3 + T_{1980}/A_3)/4$$

...

$$I_6 = (T_{1910}/A_1 + T_{1940}/A_2 + T_{1970}/A_3 + T_{2000}/A_3)/4$$

After initialization, prediction is performed by updating overall smoothing, trend smoothing, and seasonal smoothing respectively, until the end of the last season is reached.

### 5.3 Estimated Future Sea Temperature

The estimated sea temperature near Scotland over the next 50 years predicted by STM is shown as the following heatmaps that we visualized.

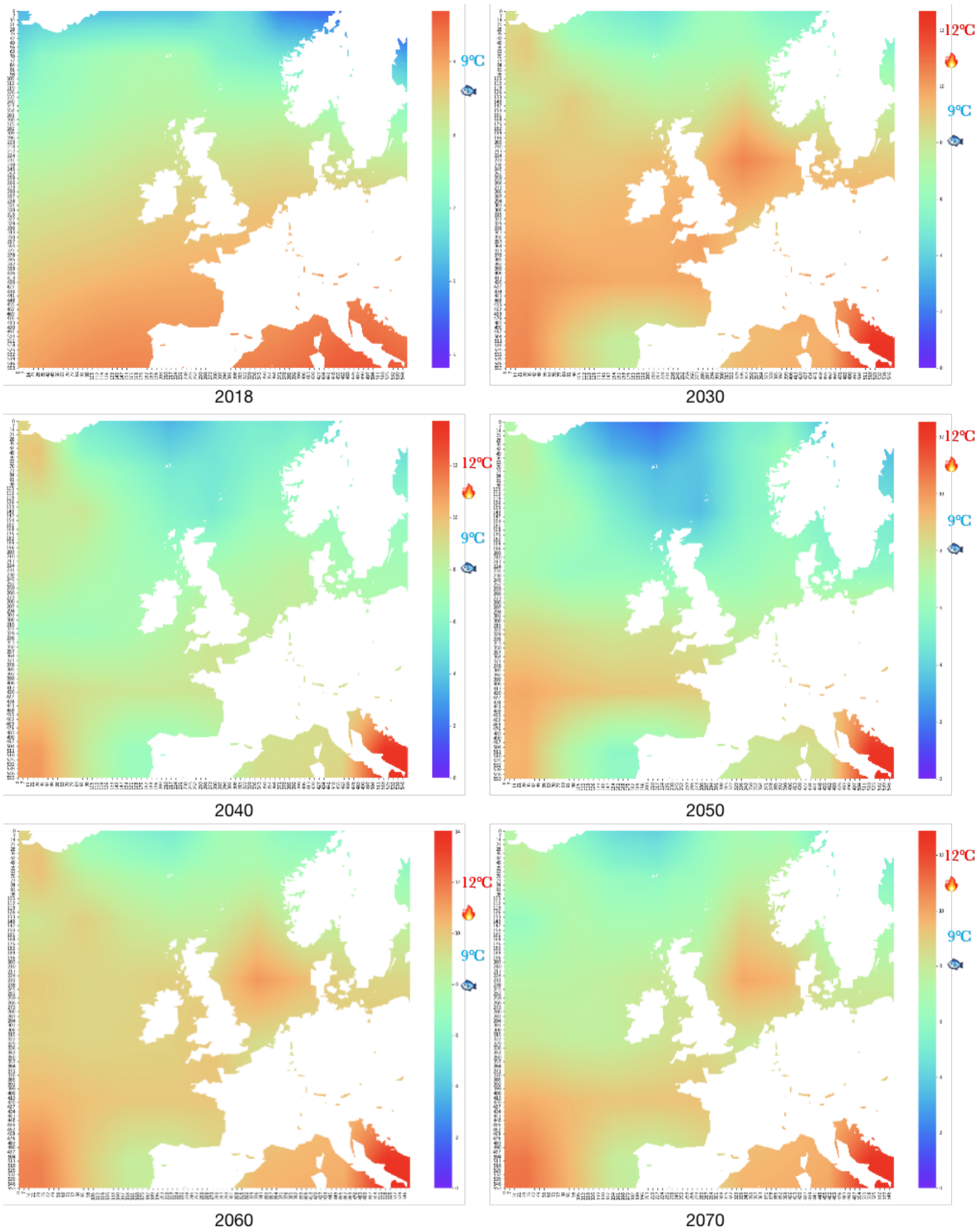



Figure 3. Heatmaps of Sea Temperature near Scotland over the Next 50 Years [2]

Note that **temperature scales of different subgraphs are NOT the same**, as we've indicated on the top right corner of each heatmap. For heatmaps of year 2030 to 2070, the most suitable sea temperature for Atlantic mackerel and herring, 9 °C [12]-[13], is marked

[2] Background is from Tencent Map.

in cyan, such that we can intuitively see the potential migration pattern.

Exact values in celsius are shown in the following table,

| | Geographical Location | | | | | | | |
|---|---|---|---|---|---|---|---|---|
| Year | (12.5°W, 57.5°N) | (7.5°W, 57.5°N) | (2.5°W, 57.5°N) | (12.5°W, 52.5°N) | (7.5°W, 52.5°N) | (2.5°W, 52.5°N) | (12.5°W, 47.5°N) | (7.5°W, 47.5°N) |
| 2020 | 8.53 | 8.64 | 9.15 | 8.46 | 7.76 | 8.21 | 9.46 | 9.06 |
| 2030 | 10.11 | 10.68 | 11.34 | 11.22 | 10.35 | 10.54 | 9.88 | 9.76 |
| 2040 | 11.16 | 12.02 | 11.92 | 11.46 | 11.70 | 11.68 | 11.29 | 11.39 |
| 2050 | 9.34 | 9.95 | 9.96 | 10.31 | 10.75 | 10.85 | 10.35 | 10.29 |
| 2060 | 11.70 | 12.19 | 11.93 | 11.39 | 11.44 | 11.20 | 10.42 | 10.34 |
| 2070 | 9.94 | 10.47 | 10.56 | 10.48 | 10.93 | 11.03 | 10.97 | 10.87 |

Table 1. Estimated Sea Temperature near Scotland over the Next 50 Years

### 5.4 Model Validation

Finally, we validated the consistency of STM by performing sea temperature estimation near a randomly selected maritime space at (25°W, 44°N) with all three data sets (HadISST, GHCN-M, EST). We normalized our results and plotted Figure 4 which vividly proves that STM is able to forecast future sea temperature in a consistent manner.

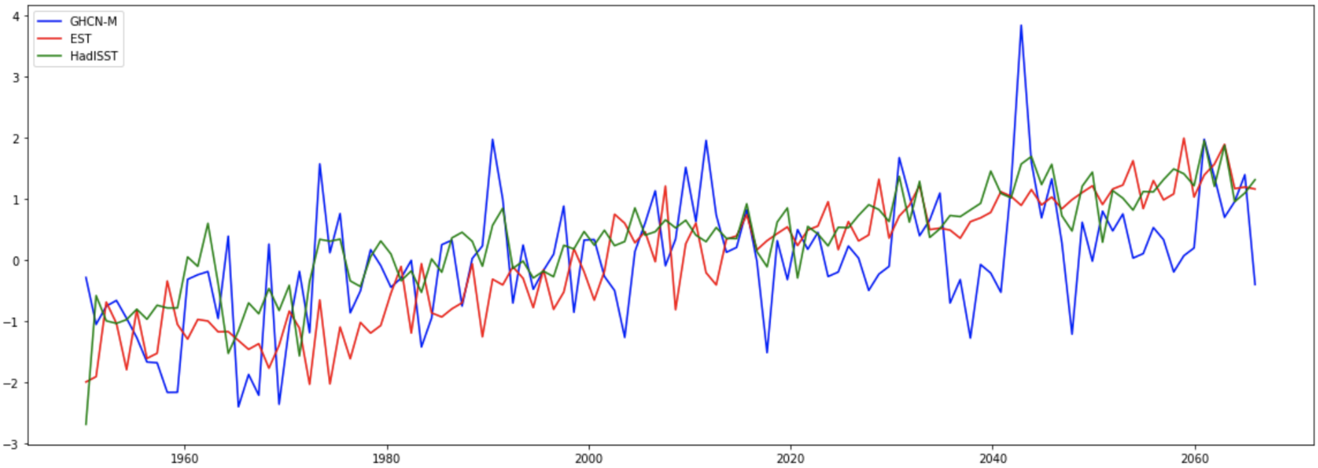



Figure 4. Normalized Prediction Results by HadISST, GHCN-M, and EST

# 6 Migration Model (MM)

## 6.1 The Probabilistic Approach for MM

After sea temperature estimation, the next task is to predict potential migration pattern of Atlantic mackerel and herring. As Assumption 2 indicates, the only factor that drives Atlantic mackerel and herring to migrate is sea temperature, therefore, we must bridge a connection between sea temperature and fish migration.

ICES-WGMEGS provides us with the distribution of Atlantic mackerel, based on this data and Assumption 1, that Atlantic mackerel and herring have the same habitats near Scotland, we visualized the habitats of these two species along with the heatmap, then further plotted the quantity of fish with respect to sea temperature as follows,

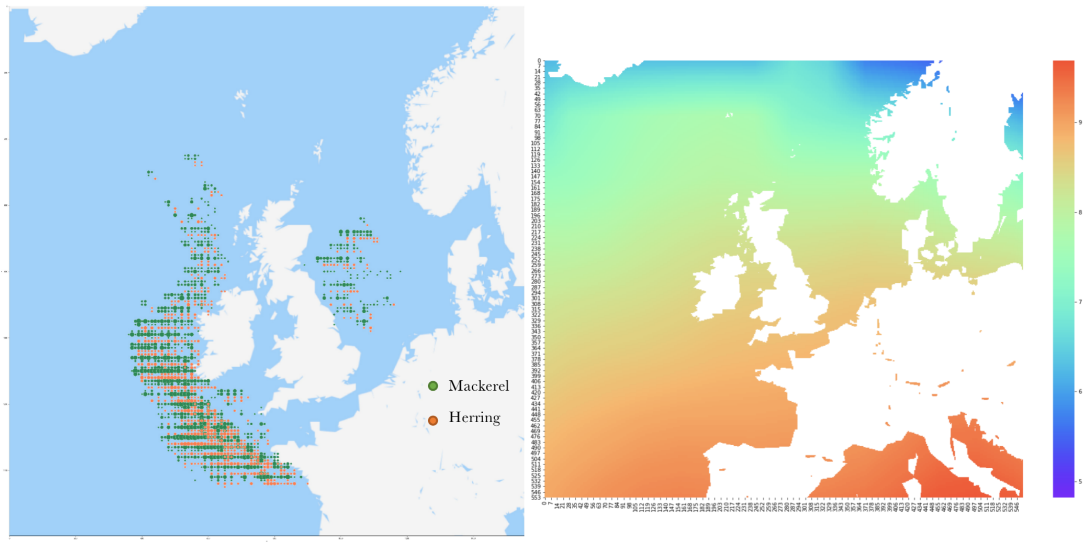



Figure 5. The Distribution of Atlantic Mackerel and Herring near Scotland & Sea Temperature Heatmap

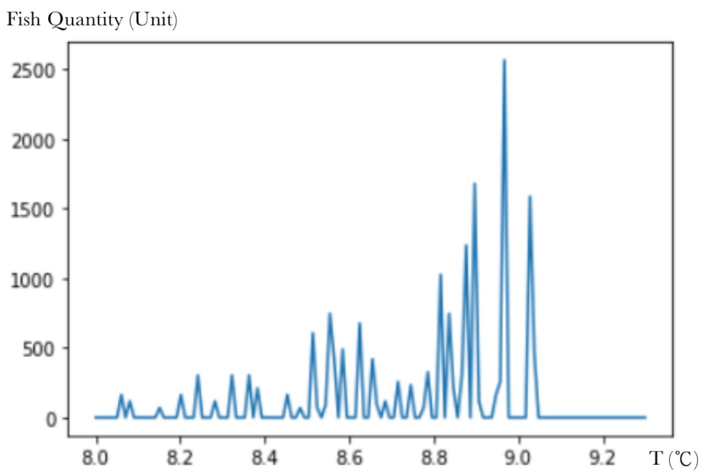



Figure 6. The Distribution of Atlantic Mackerel and Herring with Respect to Sea Temperature

We observed that as sea temperature ascents or descents gradiently such that it deviates from 9°C, the population of Atlantic mackerel and herring also declines gradiently, forming approximately a Gaussian distribution.

From the above analysis, using a probabilistic method to imitate the migration process can be the most ideal approach for us to develop MM. And this probabilistic approach should satisfy the following criteria,

- **First, waters with temperature near 9°C will have a higher probability of being the habitats**, and waters with lower or higher temperature are less likely to appeal a large fish population.
- **Second, Atlantic mackerel and herring have higher probability of migrating to waters with temperature near 9°C**, but when they are already in their comfort zones, they are unwilling to migrate, or in other words, they shows a lower probability of migration.
- **Third, fishes have a higher probability of gathering together, instead of scattering around**, because they are group living species [14].

As a result, we will implement a Markov model to simulate the migration of Atlantic mackerel and herring.

## 6.2 Markov Process[3]

To realize Markov process, we first divided the map into a uniform geographical network, such that every node represents a piece of maritime space where fishes live, rest, and reproduce. Every node is linked to its neighbouring nodes such that migration could happen over any time interval.

Assume the $i^{th}$ grid has $N_i(t)$ amount of fishes in year $t$, the fish density, $D_i(t)$, can be derived from,

$$D_i(t) = \frac{\mathrm{d}N_i(t)}{\mathrm{d}t} = \sum_{j \neq i} r_{ij}(t) N_j(t) - \sum_{j \neq i} r_{ji}(t) N_i(t) \qquad \text{(Fish Density)}$$

Where $r_{ij}(t)$ is the incoming rate from $j$ to $i$, so we can interpret the fish density, $D_i(t)$, as the difference between incoming and outgoing fish flows.

As we've observed from Figure 5 and Figure 6, the migration probability should have a Gaussian-like relationship with respect to $T_i(t)$ and $T_j(t)$, so we assign $r_{ij}(t)$,

[3] We developed our Markov process greatly based on Andrea Kölzsch, Erik Kleyheeg , Helmut Kruckenberg, Michael Kaatz, and Bernd Blasius' model [15].

$$r_{ij}(t) = \frac{T_i(t)}{T_j(t)\sqrt{2\pi\sigma_{ji}}} e^{\frac{-(T_i(t)-\mu_{ji})^2}{2\sigma_{ji}^2}} \quad \text{(Migration Rate)}$$

We can also approximate $r_{ij}(t)$ as,

$$\widetilde{r}_{ij}(t) = \frac{J_{ij}(t, t+\Delta t)}{N_j(t) \cdot \Delta t} \quad \text{(Migration Rate Approximation)}$$

Where $J_{ij}(t)$ is the migration flow written as,

$$J_{ij}(t) = r_{ij}(t) N_j(t) \quad \text{(Migration Flow)}$$

To realize our Markov process numerically, we can rewrite it as a Markov chain equation,

$$N_i(t+\Delta t) - N_i(t) = \sum_{j \neq i} p_{ij}(t, \Delta t) N_j(t) - \sum_{j \neq i} p_{ji}(t, \Delta t) N_i(t) \quad \text{(Markov Chain a)}$$

Where $\Delta t$ represents the length of time interval. We can also rewrite Markov chain as,

$$N_i(t+\Delta t) = \sum_{j \neq i} p_{ij}(t, \Delta t) N_j(t) + p_{ii}(t, \Delta t) N_i(t) \quad \text{(Markov Chain b)}$$

Where $p_{ij}(t, \Delta t)$ denotes the migration probability, suppose there are totally $n$ grids, we can derive the probability matrix as,

$$\begin{pmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,n} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{3,1} & p_{3,2} & \cdots & p_{n,n} \end{pmatrix}$$

Therefore, we can rewrite our Markov process as,

$$\begin{pmatrix} N_1(t+\Delta t) \\ N_2(t+\Delta t) \\ \cdots \\ N_n(t+\Delta t) \end{pmatrix} = \begin{pmatrix} p_{1,1} & p_{1,2} & \cdots & p_{1,n} \\ p_{2,1} & p_{2,2} & \cdots & p_{2,n} \\ \cdots & \cdots & \cdots & \cdots \\ p_{3,1} & p_{3,2} & \cdots & p_{n,n} \end{pmatrix} \begin{pmatrix} N_1(t) \\ N_2(t) \\ \cdots \\ N_n(t) \end{pmatrix}$$

Finally, we can calculate the Poincaré map, $S(t)$, from one time point to the next time point by matrix multiplication,

$$S(t) = \prod_{k=0}^{m-1} P(t + k\Delta t, \Delta t) \quad \text{(Poincaré Map)}$$

Because STM has already helped us to predict sea temperature near Scotland over the next 50 years, and we've also discovered the relationship between sea temperature and fish density, the only variable that has not been determined yet is the probability matrix. Therefore, if we assign an appropriate value to the probability matrix, then Markov process can be easily completed.

### 6.3 Estimated Future Habitats of Scottish Mackerel and Herring

By observation from Figure 5 and Figure 6, the population of Atlantic mackerel and herring with respect to sea temperature has approximately Gaussian-shaped distribution, therefore, we assigned the probability matrix value as,

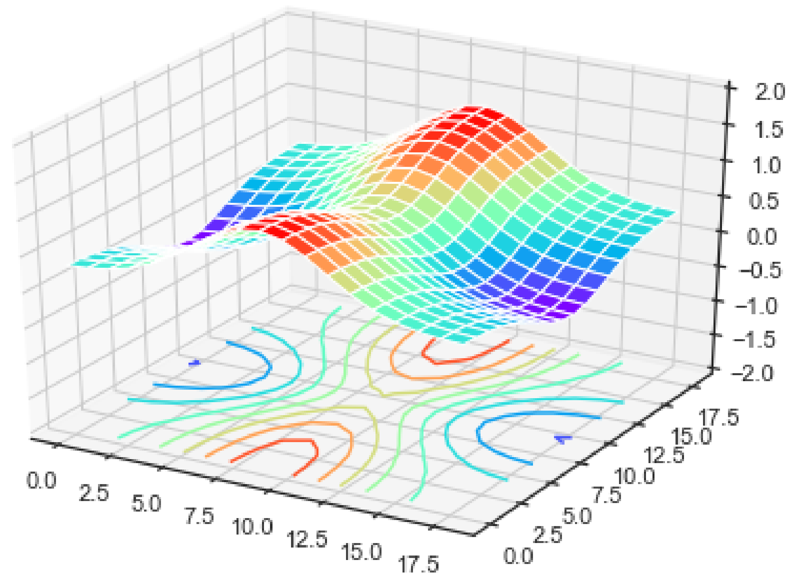



Figure 7. Visualized Probability Matrix

By ICES-WGMEGS, SSFS data sets and Eurostat Fishery Statistics, the yearly amount of herring caught in the Northeast Atlantic is about 872,327 tonnage, while the mackerel caught is about 500,188 tonnage [16]; the yearly amount of herring caught by Scottish companies is about 64,622 tonnage, while the mackerel caught is about 153,000 tonnage [1]. We used these data as a starting point and obtained the following table by simulation,

| | Amount of Mackerel and Herring Caught | | | |
|---|---|---|---|---|
| Year | Mackerel in UK's EEZ | Herring in UK's EEZ | Mackerel Elsewhere | Herring Elsewhere |
| 2020 | 153,000 | 64,622 | 374,188 | 807,705 |
| 2030 | 129,734 | 41,302 | 370,454 | 831,025 |
| 2040 | 108,541 | 54,307 | 391,647 | 818,020 |
| 2050 | 99,037 | 49,701 | 401,151 | 822,626 |
| 2060 | 102,495 | 47,247 | 397,693 | 825,080 |
| 2070 | 94,504 | 40,501 | 405,684 | 831,826 |

Table 2. Amount of Atlantic Mackerel and Herring Caught over the Next 50 Years

We also visualized the migration pattern of Atlantic mackerel and herring,

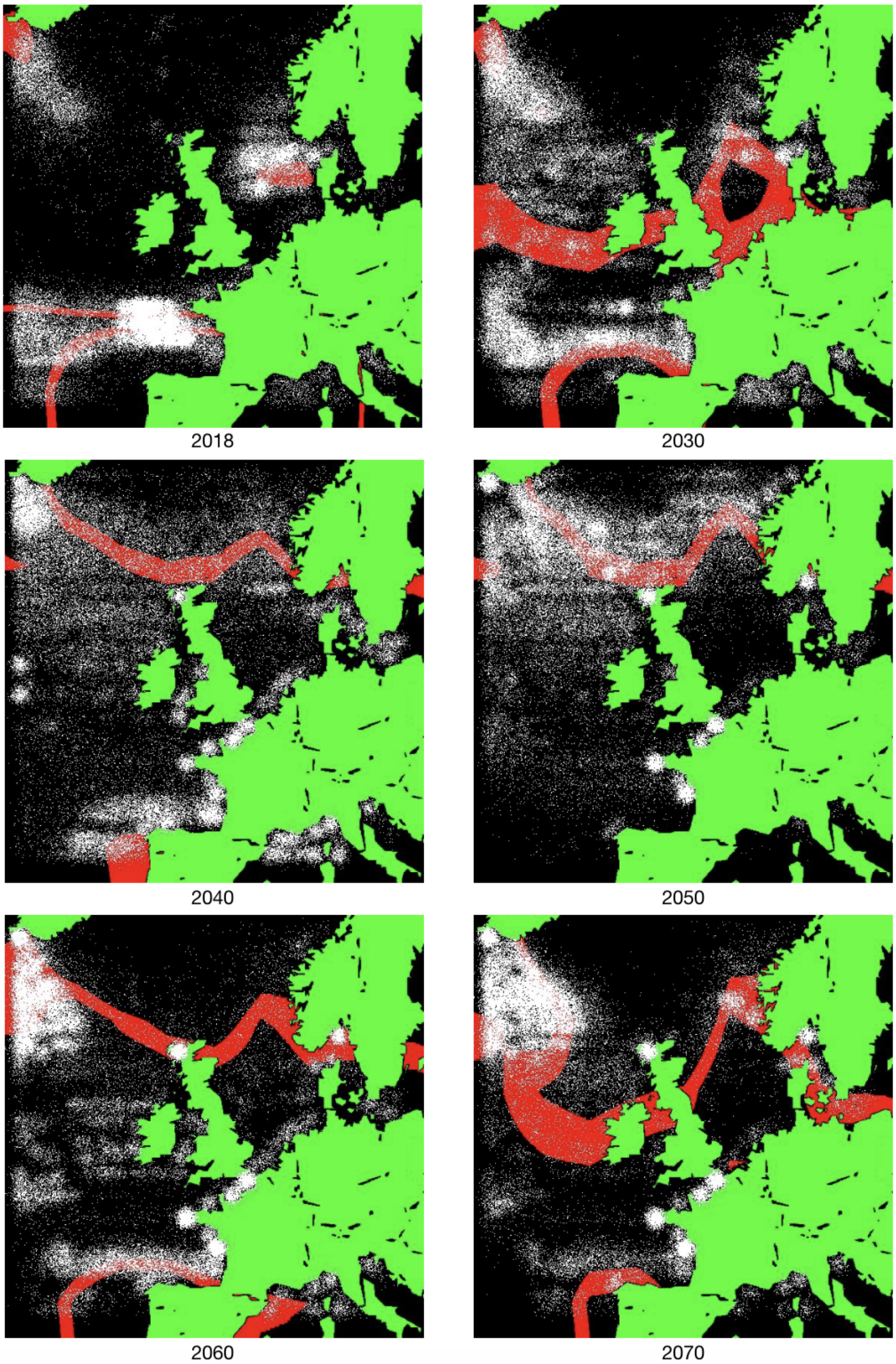



Figure 8. Migration Pattern of Atlantic Mackerel and Herring over the Next 50 Years

Note that waters with temperature near 9 °C is marked in red, land is marked in green, and fish is marked as white dots. From the diagram, we can conclude that as global warming continues, Atlantic mackerel and herring are most likely to migrate towards the Northwest maritime spaces. As a result, sea near Iceland might become the most important habitats of these two species over the next 50 years.

# 7 Fishery Profit Model (FPM)

## 7.1 Cost-Benefit Analysis

After implementing STM to simulate future sea temperature, and MM to explore potential fish migration pattern, finally, it is high time to use the predicted data and perform cost-benefit analysis in our last model, FPM, in order to find ① the worst case (shortest elapsed time), ② the best case (longest elapsed time), and ③ the most likely case (average elapsed time) until small fishing companies are no longer capable of earning profits. Beyond elapsed-time analysis, we will also use FPM to test some suggestions for Scottish small fishing companies to improve their operation and determine which of them are feasible and which are not.

We begin with the following equation:

Net Profits = Total Earnings - Total Costs

Then we divide the total costs into two parts. Namely, fixed costs and variable costs,

Total Costs = Fixed Costs + Variable Costs

According to surveys about fishing costs, we can further partition variable costs into [17]-[18],

Variable Costs = Fuel Costs + Labor Costs

We will analyze the variable costs of each vessel individually.

Denote the time from land support to location $k$ as $t_k$. The time associated with location $j$ and vessel $i$ can be approximated as,

$$T_{i,j} = \frac{t_{j+1} - t_{j-1}}{2} \qquad \text{(Time Interval for vessel } i \text{ at location } j\text{)}$$

Then, the fuel costs of vessel $i$ at location $j$ can be formulized as,

$$FC_{i,j} = T_{i,j} \times C_{i,j} \times p \qquad \text{(Fuel Costs)}$$

Where $C_{i,j}$ is the fuel consumption rate, p is the price of fuel.

The general formula of fuel consumption is,

$$C_{i,j} = P_i \times SFC \times LF_{i,j} \qquad \text{(Fuel Consumption)}$$

Where $P$ is the engine power, $SFC$ is the specific fuel consumption, and $LF$ is the load factor, which represents the engine loading relative to its maximum continuous rate, and can be calculated as [17],

$$LF_{i,j} = L_{max} \times \frac{(\frac{v_{i,j}}{d_i})^3 + \frac{L_{min}}{L_{max}-L_{min}}}{1 + \frac{L_{min}}{L_{max}-L_{min}}} \qquad \text{(Load Factor)}$$

The labor costs for vessel $i$ is defined as

$$LC_i = N_i \times w_i \times C_i \qquad \text{(Labor Costs)}$$

Where $N_i$ is the total number of days at sea for vessel $i$, $w_i$ is the labor costs per day per crew member, and $C_i$ is the estimated crew size of vessel $i$ [17].

As for earnings, we can get the revenue per unit energy by,

$$Rev = \frac{TotalRev}{E} \qquad \text{(Revenue Per Unit Energy)}$$

Where $TotalRev$ is the total revenue and $E$ is the total energy consumed. We assume that in each trip, the amount of fishes caught is proportional to the local fish density. Then the total revenue can be expressed by,

$$TotalRev = \rho_1\alpha + \rho_2\beta \qquad \text{(Total Revenue)}$$

Where $\rho_1$ is the density of herring, $\rho_2$ the density of mackerel; $\alpha$ is the price of herring, $\beta$ the price of mackerel. Therefore, for vessel $i$, the revenue at location $j$ is given by,

$$R_{i,j} = Rev \times E_{i,j} \qquad \text{(Revenue at Location } j \text{ for Vessel } i\text{)}$$

Finally, to obtain total profits, we just need to compute the difference between total revenue and total costs. Further, because we've derived the equations for individual vessel's costs and earnings, therefore, we can even simulate each vessel's fishing process.

We conducted 100 simulations and our results are,

- ① the worst case (shortest elapsed time) is that Scottish small fishing companies can no longer earn profits in 3 years (elapsed in 2023).
- ② the best case (longest elapsed time) is 45 years (elapsed in 2065).
- ③ the most likely case (average elapsed time) is 18.79 years (elapsed between 2038 and 2039).

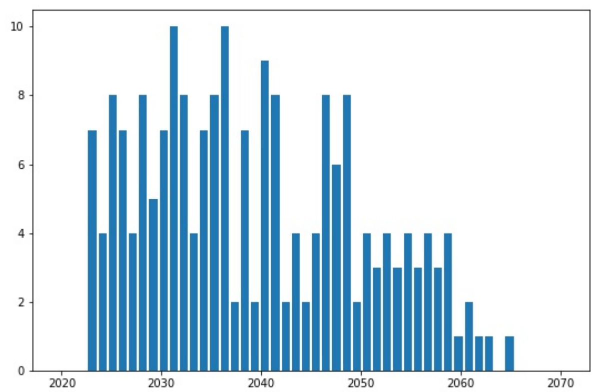



Figure 9. The Elapsed Time When Scottish Small Fishing Companies Earn No Profits

## 7.2 Suggestions for Small Fishing Companies

We tested multiple strategies and chose the best three for Scottish small fishing companies to improve their profits. The first strategy is to replace small vessels with the big ones. Because compared to a small vessel, a large vessel is capable of both catching more fishes and lowering unit cost.

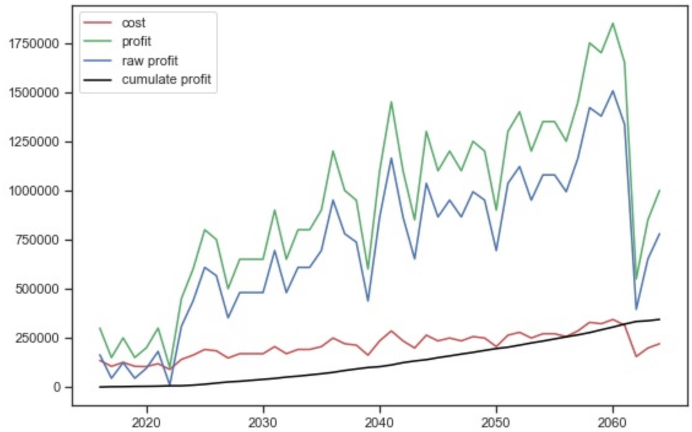



Figure 10. The Annual Costs, Earnings, Net Profits, and Cumulative Profits of Large Vessels[4]

The second strategy is to fish in high seas. This is because as global warming is constantly heating waters near Scotland, Atlantic mackerel and herring are migrating out instead of staying in the same habitats as before.

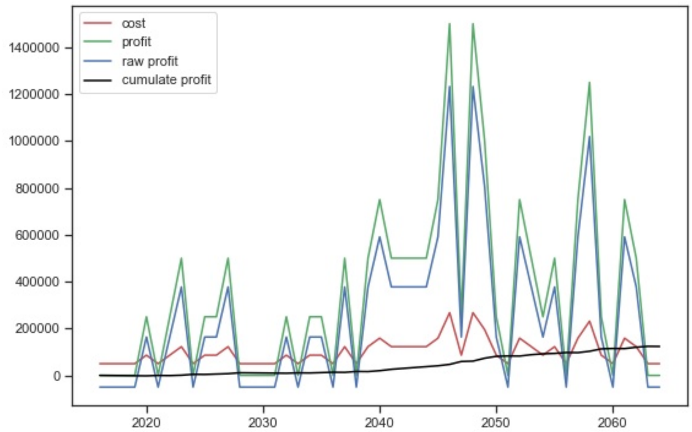



Figure 11. The Annual Costs, Earnings, Net Profits, and Cumulative Profits of High Sea Fishing

[4]Notice that in these graphs, value of the cumulative profits (marked in black) is the actual value divided by 1,000.

The third strategy is to relocate assets. The reason for this strategy is exactly the same as the second strategy, that is, global warming makes Scotland no longer a suitable habitat for Atlantic mackerel and herring. As we've obtained from MM, compared to Scotland, Iceland becomes a better choice over the next 50 years.

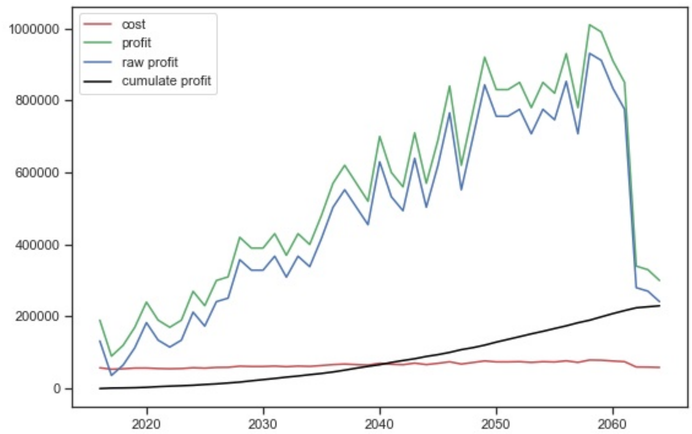



Figure 12. The Annual Costs, Earnings, Net Profits, and Cumulative Profits of Relocation

## 7.3 The Impact of Migration into the Territorial Waters

Lastly, we are going to discuss what will happen and how will our proposal been affected if a proportion of Atlantic mackerel and herring migrates into the territorial waters.

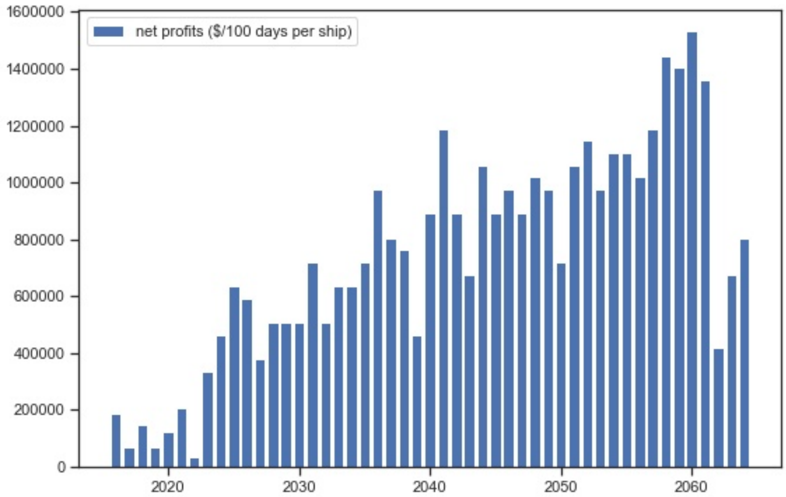



Figure 13. The Annual Profits by Fishing in the Territorial Waters

We simulated how annual profits will vary as Scottish small fishing companies change their fishing ground from the UK's EEZ to territorial waters, and the result indicates that as the profits of fishing in the territorial waters boosts year by year, the profits of fishing in the UK's EEZ declines accordingly. However, because our report suggests small fishing companies to fish in high seas instead of coastal waters, the impact of fish migration into the territorial waters is relatively limited.

## 8 Sensitivity Evaluation

The sensitivity evaluation of STM is performed in Section 5.4, where Figure 4 illustrates the consistency of STM beacuse estimations from all three data sets (HadISST, GHCN-M, EST) show the same trend and seasonality.

The sensitivity evaluation of MM is conducted by changing the probability matrix. From Figure 14, we can conclude that although the distribution of Atlantic mackerel and herring may vary significantly with the change of probability matrix, MM still simulates an ideal result, because fishes still migrate towards waters with 9 °Ctemperature.

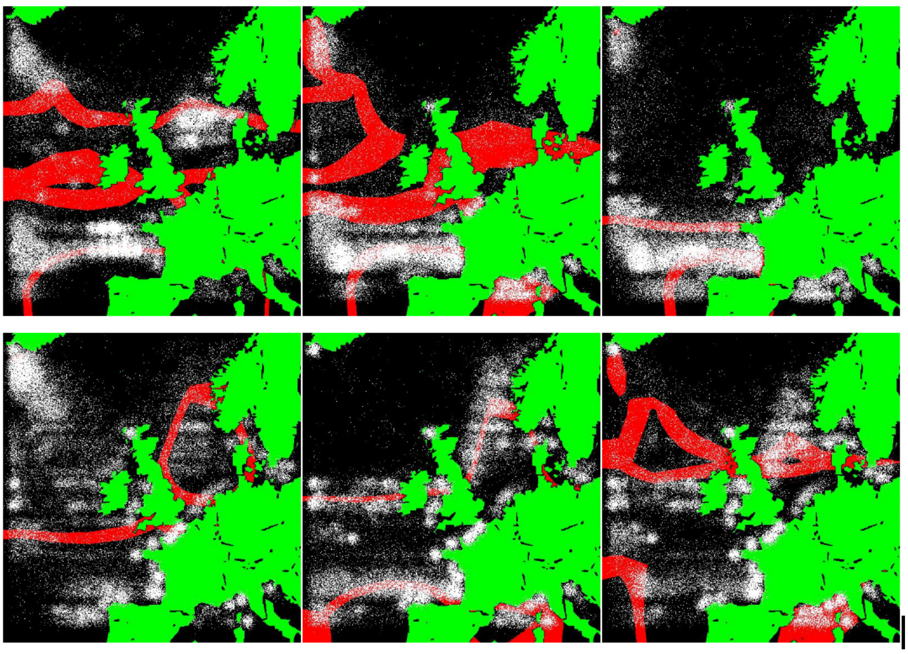


Figure 14. Sensitivity Evaluation of MM

The sensitivity evaluation of FPM is carried out by varying parameters of individual vessels, such as speed, capacity, and navigational distance. For example, Figure 15 indicates that as a vessel's navigational distance increases, the annual fishing costs will increase accordingly.

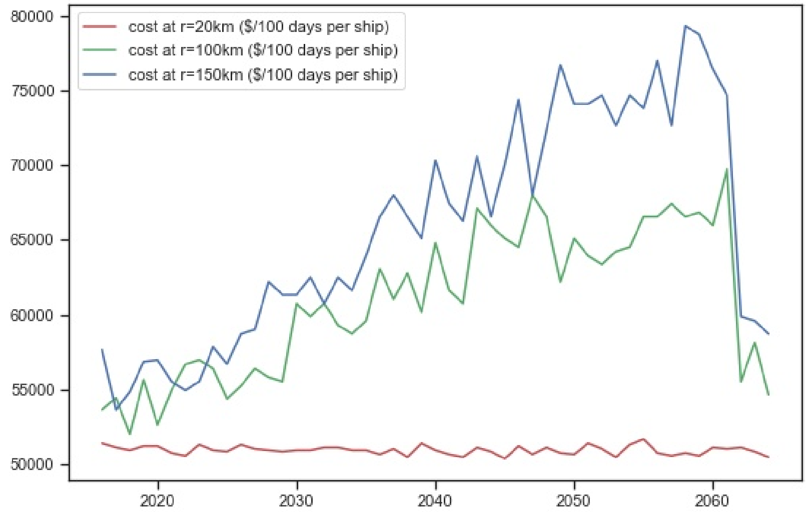



Figure 15. Sensitivity Evaluation of FPM

# 9 Strengths and Weaknesses

## 9.1 Strengths

- **We utilized large amount of authoritative data, and implemented data visualization to help readers get a more intuitionistic understanding of our reasults**. In conclusion, the extensive use of various data makes the report more convincing and applicable for real world scenario.
- **Sea temperature predicted by time series analysis maintains trend and seaonality**. For periodic variables with tendency, time series analysis by Holt-Winters' method is capable of maintaining these characteristics, therefore, STM is able to forecast more reasonable sea temperature data.
- **Markov process gives a highly-accurate prediction for future habitats of Atlantic mackerel and herring**, since it divides a long time period into small time intervals, and realizes a probabilistic approach for simulating change between small time intervals.

## 9.2 Weaknesses

- **Sea temperature is the only factor that causes Atlantic mackerel and herring to migrate in MM**, however, in reality, other factors such as ocean currents, food, and seawater salinity are also essential factors in fish migration.
- **The habitats of mackerel and herring are the same**, since we assume these two species share the same preference for environmental variables, but actually they have many distinctive habits that may challenge our assumption.

- **The total fish population will not change over time**, because we suppose the high reproduction rate offsets loss. However, owing to sea pollution, overfishing, and other negative reasons, the amount of fishery resources is facing imminent crisis.

## 10 Conclusion

In conclusion, to satisfy the requirements from the Scottish North Atlantic Fishery Management Consortium, we developed three models , and successfully solved the big problem by decomposing it into two small subproblems,

- The first model, Sea Temperature Model (STM), is utilized to estimate sea temperature near Scotland over the next 50 years. By implementing time series analysis with Holt-Winters' seasonal forecasting method, we ensure the trend and seasonality of sea temperature data are well maintained. Finally, we visualized the estimated data as an intuitionistic way to understand the change of sea temperature.
- The second model, Migration Model (MM), implements Markov process to simulate the future habitats of Atlantic mackerel and herring. We used sea temperature data obtained by STM to perform simulation, and uncovered the potential migration pattern of Atlantic mackerel and herring.
- The third model, Fishery Profit Model (FPM), analyzes the shortest (3 years), longest (45 years), and average (18.79 years) elapsed time until small Scottish fishing companies could no longer benefit from current operation. Also, we performed cost-benefit analysis and put forward three suggestions to these small fishing companies, namely, shifting to larger vessels, fishing in high seas, and relocating assets to Northern regions such as Iceland.

## 11 Article for *Hook Line and Sinker*

Dear *Hook Line and Sinker*,

We are glad to hear that you are willing to provide a platform to help fishermen understand the seriousness of the change of sea temperature, and we are very proud to have the chance to share our solutions to improve your readers' future business prospects.

Atlantic herring and mackerel are two important species that create considerable profits for small local fishing companies. However, with the increase of sea temperature, they may migrate north to other waters and no longer come back again. As a result, the costs for fishing may ascend accordingly (e.g. time, fuel, labor), while the profits may also decrease sharply. If we could not stop unfortunate things from happening, then small fishing companies may eventually go bankruptcy thus influening all fishermen's living. In this case, a strategy that can find a new way of fishing is in urgent need.

We strongly advice you to replace small vessels with big ones. Because in our fishery profit model, larger boatload means larger power and larger capacity. We picked up boatload of 2, 4, and 16 tons and discovered fishing profits will increase as the boatload becomes larger. Additionally, though the cumulative profits curve, we can also verify that in the future, large fishing vessels with more boatload are more preferable, compared to small vessels.

Also, we recommend fishermen to fish in high seas. With our time series sea temperature prediction model, we can forecast the temperature distribution in the future. Further, our result shows that with the increase of sea temperature, global warming will push herring and mackerel to high waters. Also, we obtained the result that the revenue from fishing in high seas is dominant over fuel costs and labor costs. Hence, we strongly suggest your fishermen to catch fish in high seas where there are abundant fishery resources.

Our last finding is that relocation of assets can be a useful way to imrove profits. We assume fishing vessels will return to the coast four days one time. The cumulative profits remains zero, which means that the revenue from fishes counteract the costs. As a result, we can conclude that Scotland is no longer suitable for herring and mackerel's survival. As we can see from our migration model (MM), Iceland gradually becomes a better habitat in the future.

We hope that our effort can make fishermen realize the seriousness of the global warming problem, and take necessary actions to prevent potential loss. We also hope that all small fishing companies can develop steadily and healthily.

Yours sincerely,

Team #20200913

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