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How to Keep Scottish Fishery Industry Thriving:
Prediction of Fish Migration Caused by Ocean Temperature Change

Option #3: Moving North

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Summary Sheet

Prediction of Fish Migration Caused by Ocean Temperature Change

Melting glaciers, rising sea levels, scrambling wildlife, disappearing forests: these are all the "returns" human beings have to face wildly and furiously polluting the environment for the past century. For now, people in Scotland are already facing some serious and intractable issues brought along with the negative impacts of global warming. Mackerels and herrings are the two main targets for the Scottish fishing industry. However, due to rising sea temperature, the two types of fish are forced to migrate north to those oceanic areas that have the temperature aligned with their suitable living temperature. This will impact the fisheries with no doubt. To help small fishing companies adjust fishing range, improve on-board facilities, and prevent from loss, we build a model predicting the migration locations and general pattern for both mackerels and herrings over the next 50 years.

To model the future distribution areas of mackerels and herrings, we first predicted the temperature change of the oceanic area mainly focused on. By subdividing the area into small grids, we built prediction intervals and expected values for the temperature every year of each small grid for future 50 years based on the past data we collected from 1981 to 2015.

With the temperature prediction model, in each year, we found the migration locations of mackerels and herrings by selecting those grids that have their water temperature overlapping with the suitable living temperature of the fish. With the dots being plotted, it displays a general picture of the distribution area for both types of fish.

To show that there happens to be a migration pattern northward for both species, we combined the main distribution areas across years to make comparisons. We validate our model by combining the actual distribution of the two types of fish with historical data and the distribution we predicted from 2016 to 2070.

For every year, we also compared the distribution area to the current fishing range of the small fishing companies. Consequently, we can conclude the specific year that the mackerels or herrings will be too far away for the companies to harvest in the most likely case, best case, and worst case.

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1. Introduction

1.1 Problem Background

Global warming is a serious problem the world is now facing. The temperature of the earth's atmosphere and oceans has greatly risen due to the greenhouse effect. According to NOAA, it is stated that the average temperature of the global ocean surface has increased by approximately 0.13°C every 10 years in the past 100 years. However, marine organisms can only survive in relatively stable temperature environments that are suitable for themselves, and most of them are exceedingly sensitive to temperature changes. Needless to say, ocean temperature changes have a significant impact on the majority of marine species, as they are under the pressure of looking for more suitable habitats under the current condition.

Meanwhile, in Scotland, fishery is one of the main sources of income. In 2020, Scottish vessels landed 153 thousand tons of sea fish worth more than a million pounds, and a considerable percentage of local people depend on fishery for a living. In particular, the two main fish targets for Scottish fishing companies are mackerels and herrings. According to the statistics provided by the Scottish government, these two types of fish have boosted the real term value of their country's fishery by 42.8% in simply one year. Mackerel, the most treasured specialty of Scotland, accounted for 76% of the output value and on-board quantity. Similarly, herring composed about 20% of the oceanic landings by Scottish vessels.

1.2 Problem Summary

As we stated, since most of the fish are constantly migrating to different locations due to temperature changes, the fishery industry in Scotland is encountering a severe problem: they might be unable to catch the fish with their current fishing range. Since the fishing companies are under the limitation of on-board facilities, they must be back on the same day to ensure the freshness of the fish, which makes their fishing range impossible to expand for now. In this paper, we will mainly focus on two types of fish that are mentioned above: mackerel and herring. In order to help the companies in Scotland, we need to gain a better understanding of the migrating positions of mackerels and herrings over the timespan. In particular, we are developing a mathematical model to predict the change in the locations of both mackerels and herrings as time elapses. With the model, we then compare the fishing range of the small companies in Scotland to provide them with a precise estimation of when the fish will be out of the range and corresponding solutions.

1.3 Basic Information of the Fish:

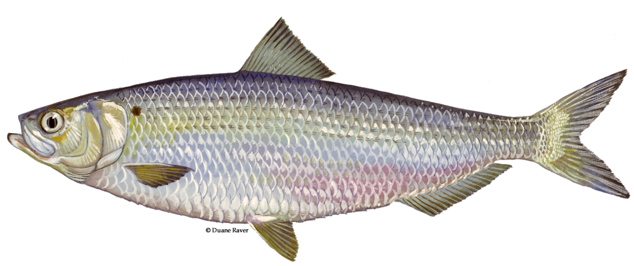
Mackerel:

Picture of the Mackerel

Mackerels are oftentimes found in temperate and tropical seas. As shown, they typically have vertical stripes on their backs and deeply forked tails. Many are restricted in their distribution ranges and live in separate populations as they are greatly sensitive to temperature change and environmental conditions.

Apart from some basic information, for this paper, it is very important to highlight the main distribution areas and the suitable living temperature for mackerels. According to the Scottish Navy, this kind of fish lives around (5°E, 58.5°N), an oceanic area near Scotland. Moreover, the suitable temperature for mackerel is about 8.86 ~ 9.6°C.

Herring:



Picture of Herring

Similar to Mackerels, herring also choose their habitats in shallow and temperate waters of the North Pacific Ocean or North Atlantic Oceans. They mostly live in inshore waters at a depth of about 200 meters and move in schools if migration is needed. As shown, herrings are small-headed, streamlined, colored fish with silvery iridescent sides and deep blue, metallic-hued backs.

In general, herrings are mainly distributed in the area around (1.3°W, 60°N), which is not very distant from the ideal habitats of mackerels. Moreover, they can only survive in the water temperature from 8.8 ~ 9.8°C, meaning that they would choose their habitats only based on temperature.

1.4 Key Terminologies

Small fishing companies: fishery companies using small fishing vessels without on-board refrigeration to harvest and deliver fish, each sail would usually be less than a day to ensure the freshness of the fish

MSE (Mean squared error): In statistics, the MSE is a measure of the quality of an estimator; it measures the average of the squares of the errors.

$\mathbf{x_h}$: The predictor's value

$\hat{y}_h$: The "fitted value" or "predicted value" of the response when the predictor is x_h

$t_{(1-\alpha/2, n-2)}$: The t-multiplier, namely, “critical t-value”

$\sqrt{MSE \times \left(1 + \frac{1}{n} + \frac{(x_h - \bar{x})^2}{\sum(x_i - \bar{x})^2}\right)}$: Standard error of the prediction

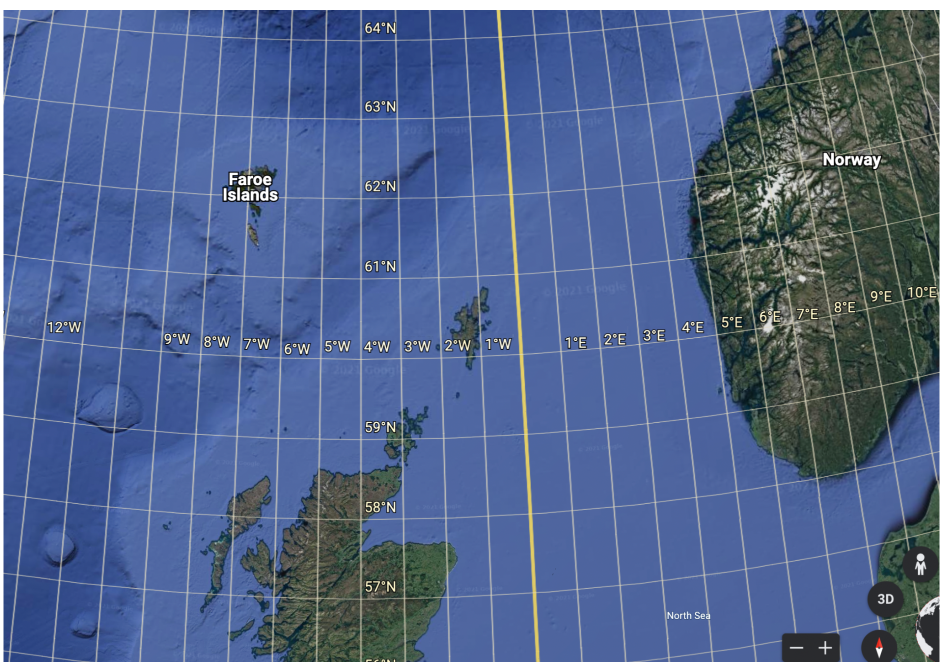
2. Assumptions

- Most importantly, we mainly focus on the sea surface temperature in the range of 12°W to 10°E in longitude and 50°N to 80°N in latitude.
- The suitable temperature of the fish will not change and the fish migrate to the sea area where the temperature is suitable.
- We consider all the fishes to be the same age, size, and swimming capacity. Furthermore, the density of fish in each district/grid is uniform.

- We assume that both species will not go extinct in the next century and either the prey or predators of mackerels and herring will not go extinct as well.
- Humans have a certain sense of conscience, so in our model, human activities such as water pollution and overfishing will be neglected.
- Natural factors such as volcanic eruptions and earthquakes are ignored.

3. Research Idea

In this part, we will present a picture of how our model is applied to locate the migration position of both mackerels and herrings. Based on our assumption, we subdivided the oceanic area of "12°W ~ 10°E, 50°N ~ 80°N" that we planned to focus on into small regions. For each region, it is of the size 1 degree in longitude and 1 degree in latitude, so there are in total 660 grids for this area. Furthermore, we have collected past data on the temperature of each small grid from 1981 to 2015 based on this dataset, we can perform predictions of the future temperature for every region in the next 50 years till 2070 (Since we failed to find the data for the ocean temperature of this area from 2015 ~ 2021, we also applied predictions for this time range). To include randomness, we used prediction intervals to consider the best case and the worst case since some extraneous variables might also affect the prediction. For the most likely temperature for each year, we simply employed the expected value from our model.



Divide the area “12°W ~ 10°E, 50°N ~ 80°N” into 660 small regions

To find the corresponding migration locations of the fish, we need to connect with the suitable living temperature for the two types of fish (8.86 ~ 9.6°C for mackerels and 8.8 ~ 9.8°C for herrings). Aligning with our assumption, the living temperatures for both types of fish are stable, and they always migrate to the location that is suitable for them to live; hence, we can pinpoint the location of both species each year by filtering which of those small regions have the temperature range that overlaps with the suitable living temperature for that type of fish. If the predicted temperature lies in the range of the suitable temperature, it means that this region is a potential migration location for the fish in this year. Finally, we will compare the position we obtained from the model with the fishing range, which is constant throughout the timespan, to see if the fishing company is still able to catch the fish.

4. Model Development

As stated, our prediction model is dependent on two parts: the temperature prediction model and the fish migration location model. To construct the model, we applied R language in R Studio for both of them, but corresponding to different libraries and methods in R.

4.1 Temperature Prediction Model

In order to predict the future temperature for every grid, we used the data set collected which includes the temperature data of this ocean range from 1981 to 2015. For randomness, we selected the prediction interval method in R which can provide us with an interval of temperature for each grid in each year rather than a deterministic value. To be more specific, a prediction interval is a type of confidence interval (CI) used with predictions in regression analysis; it is a range that predicts the value of a new observation, based on our existing model. This below is the general formula for the prediction interval.

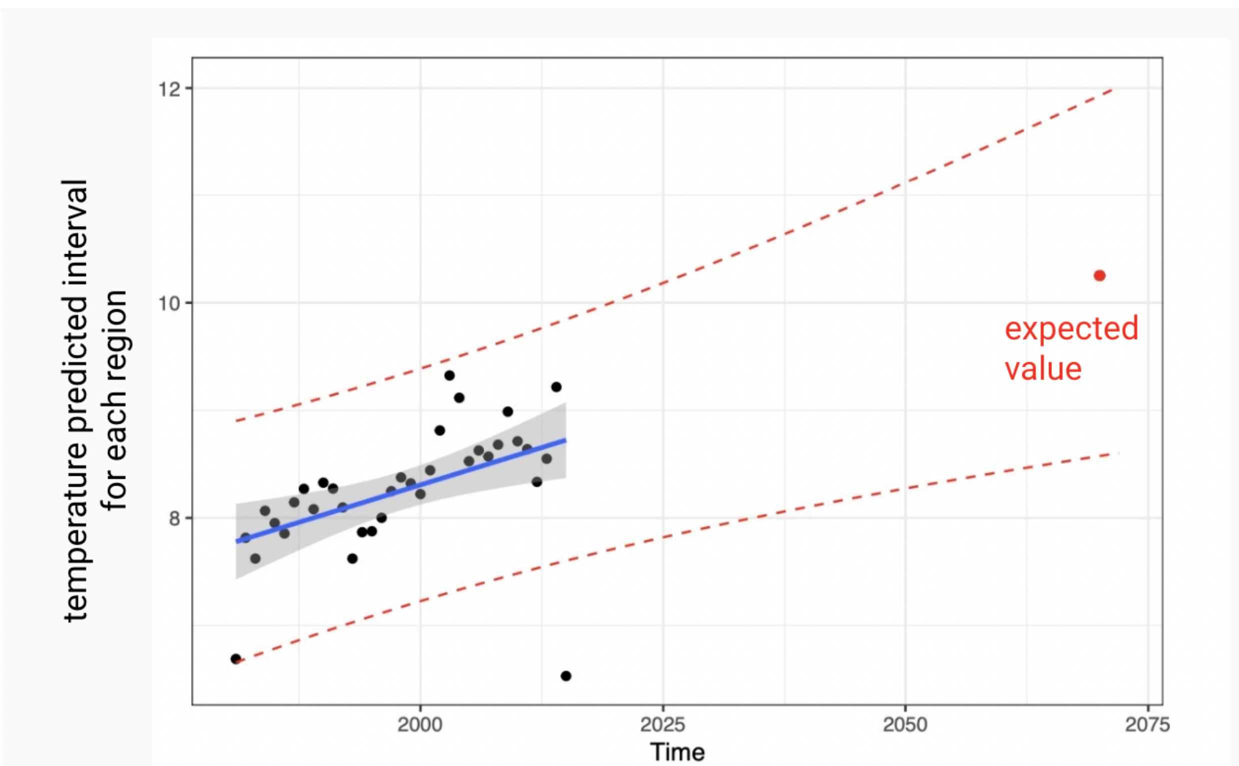
The general formula in words:

Sample estimate ± (t-multiplier * standard error)

And the formula notation is:

$$\hat{y}_h \pm t_{(1-\alpha/2,n-2)} \times \sqrt{MSE \times \left(1 + \frac{1}{n} + \frac{(x_h - \bar{x})^2}{\sum(x_i - \bar{x})^2}\right)}$$

Applying this to our case, the temperature prediction interval is built with the actual observed temperature data from the past 20 years, and it can display a range of temperature in the future for every year. The graph below displays the predicted temperature interval and expected value for one small region in 2070. For each year, in order to confirm the migration position at that time, we need to have a predicted interval and expected value for every region. Hence, we have in total modeled on 660 (regions) *55(years) to inspect the change of temperature through timespan and locate the positions of mackerels and herrings.

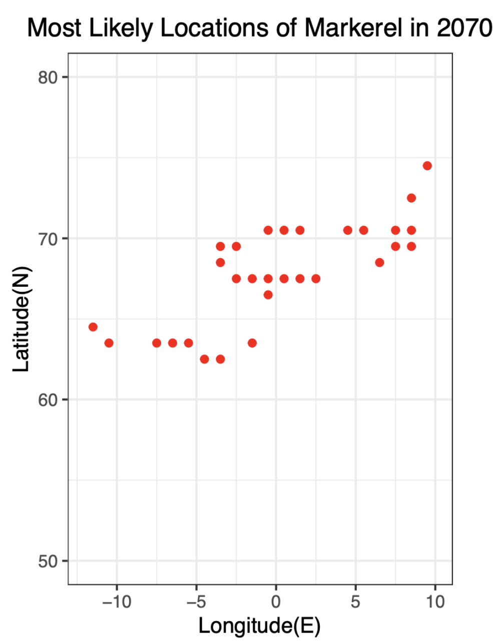


2070 Temperature Prediction Interval and Expected Value for One Region

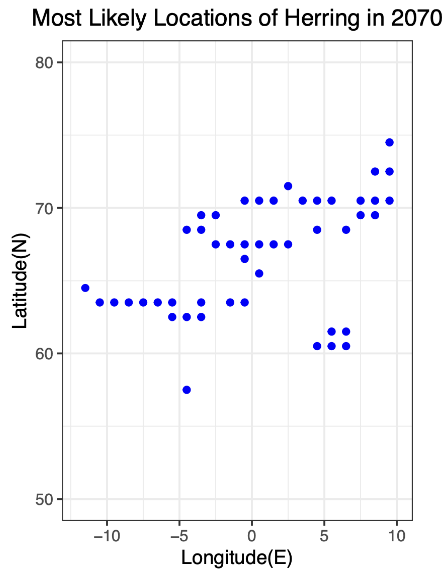
In addition, based on the comparison of the temperature across time for one region alone, we can also conclude that the temperature of the ocean area that we are interested in gradually increases with time. From the graph above, the estimated temperature in 2070 is much higher than the actual data of 1981~2015 we collected and modeled on, that even the lower bound is almost as high as before. Therefore, this also confirms our statement that the temperature of the water is rising greatly for this region over the years.

4.2 Fish Migration Location Model

As we have already constructed the model on the temperature prediction interval and expected temperature for each region, we can then build our fish migration location model. For this model, we will have longitude on the x-axis and latitude on the y-axis to imitate a flat view of the earth for this region. If one squared region is chosen to be the potential living location for either type of fish, we will plot a dot corresponding to its location on the graph. To model the possible fish migration location for one specific year, we can select the regions that have the temperature overlap with the suitable living temperature of the mackerels to result in the positions of them, and similarly, the herrings. For a simpler case, we first focus on the most likely temperature, the expected value, of each grid. If the expected value of one grid is between the range of 8.86 and 9.6, it means that the grid is a possible living location for mackerels in that year; therefore, we select that region, and a dot thus appears on the corresponding location in our graph. Otherwise, either the expected temperature is below or above the suitable living range, we



would consider the grid to be impossible for the fish to survive, thus would not be displayed in our dot graph below.

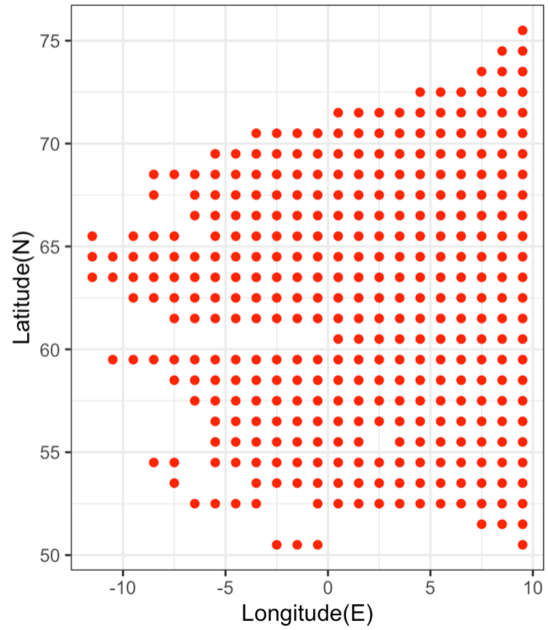


The above shows the most likely locations of mackerels in 2070. Even though we do not have a comparison of the locations across the years or with the fishing range of the companies at this point, we can have a general idea of what possibly the distribution area of mackerels will be like in 2070.

Similarly, we also applied this process to locate the position of the herrings in 2070. The only step that needs to be revised is when selecting the temperature, we should change the range to 8.8 to 9.8, which is the suitable living condition for herrings. Therefore, we generate the graph below providing us with a picture of where herrings are mainly distributed in 2070.

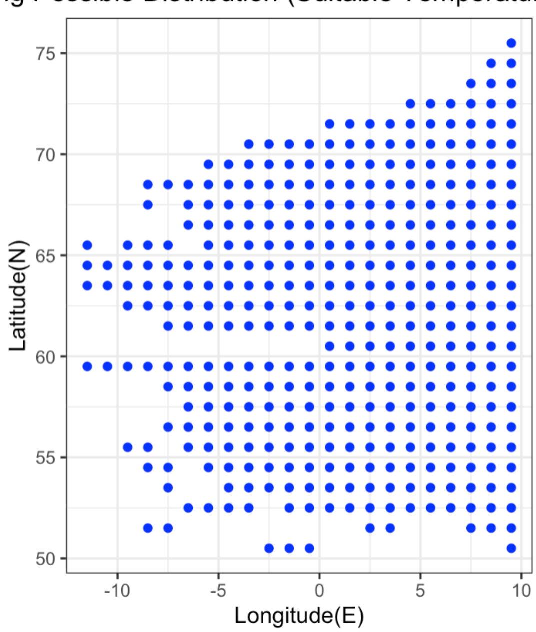
While this above is the simple case where we merely compare the expected value with the suitable living range, we should also apply the interval we resulted from the temperature model into the prediction of fish location. In this case, the interval of temperature ensures some randomness to be included rather than a deterministic result. To perform this, for example, for mackerels in 2070, we select the interval that has its lower bound smaller than 9.6 and upper bound greater than 8.86, then we plot a dot on the conceptual "map" we created; otherwise, we abandon the location since it cannot be considered as a possible location.

Mackerel Possible Distribution (Suitable Temperature) in 2070



Similarly, the process is repeated for herrings. In 2070, if one region has the lower bound of the temperature interval smaller than 9.8 and the upper bound greater than 8.8, it would be viewed as a likely migration position for herrings. If we plot the distribution of herrings based on this mindset, we would result in the graph below.

Herring Possible Distribution (Suitable Temperature) in 2070

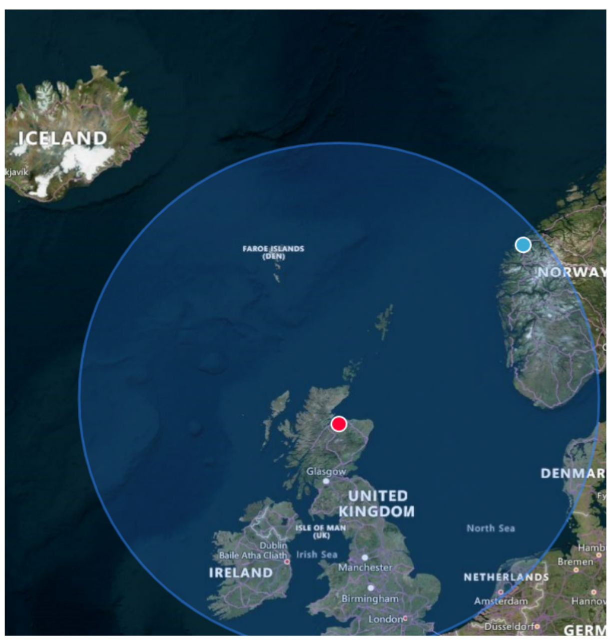


5. Application of the Model

In this part, we will apply the temperature prediction model to real-world questions encountered by the fishery industry in Scotland; specifically, we will focus on small fishery companies to see how they might adjust to this northward migration of mackerels and Scottish herrings. The primary concern of small fishery companies is that both species might migrate out of their fishing range after decades. This is because these companies use fishing vessels without on-board refrigeration, which means they must return to the harbor or the market within a day to ensure the freshness of the harvested fish. Comparing the locations of both species over the next decades and the fishing range of small companies, we will obtain the elapsed time of both species out of the fishing range.

5.1 Current Location of Fishery Companies

Fishery is one of the most prosperous and profitable businesses in Scotland: according to the Scottish government, there were 2,098 active registered fishing vessels in 2019; these enterprises are scattered across Scotland but mainly around Aberdeen, central, southern Scotland, and Highlands and other islands, according to the Royal Society of Edinburgh. In our model, we will assume that all these companies are located in Inverness (57.4908° N, 4.2331° W), both the capital of Highland and an important harbor.

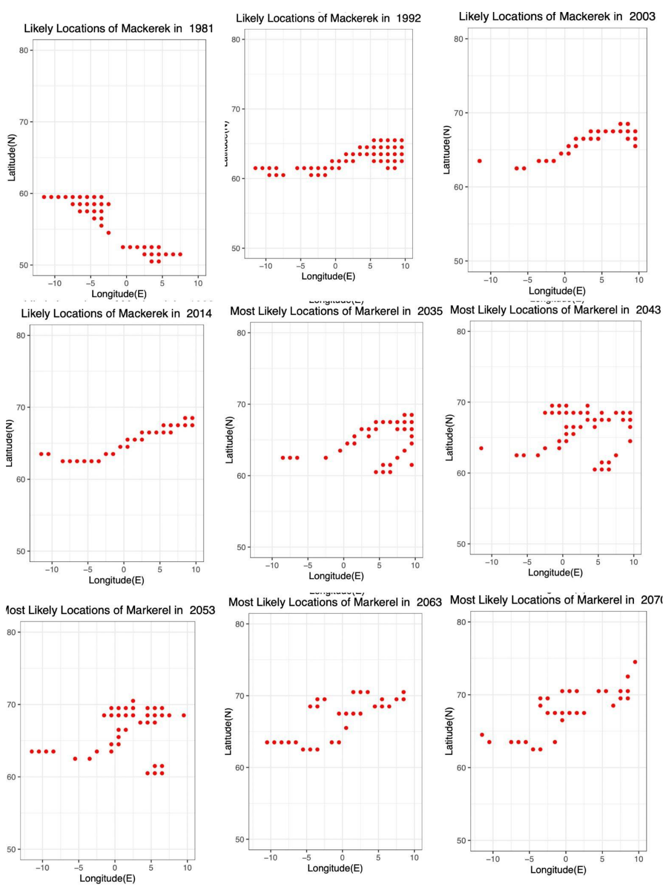


5.2 Fishing Range of Small Fishery Companies

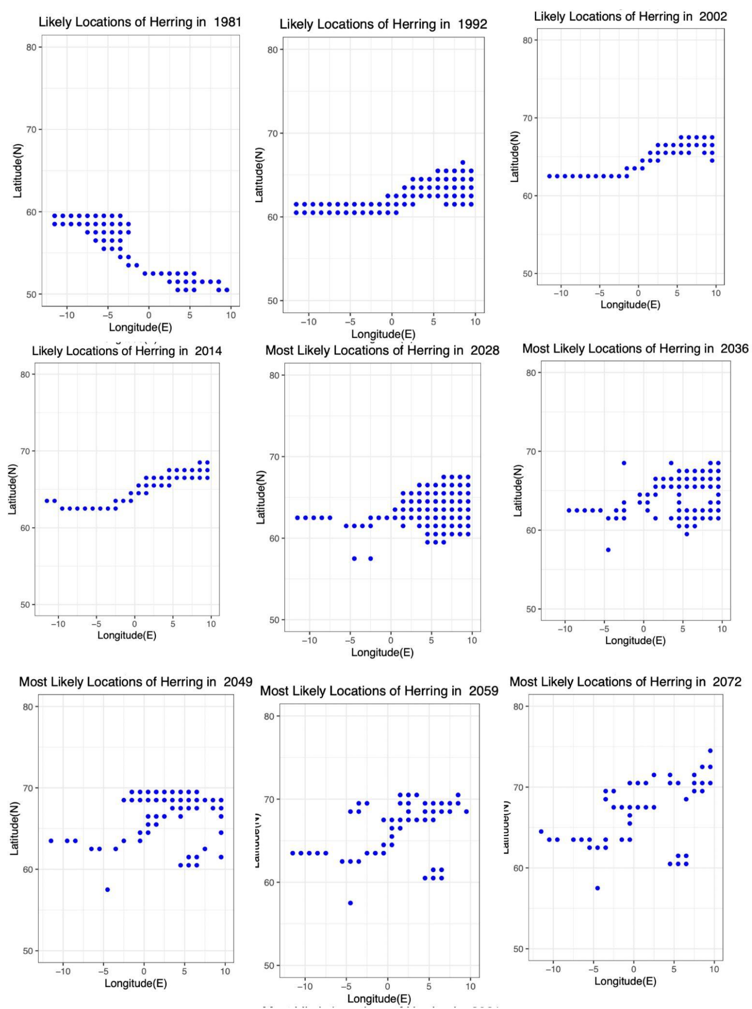
The fishing range is estimated using the amount of fuel carried by each vessel. According to some vessel owners, 1 gallon of fuel would enable 3 miles of traveling; in another word, if a vessel carries 500 gallons of fuel for each sail, which would enable 1500 miles of traveling with 500 miles of backup fuel, we consider the average travel range of small vessels to be 1000 miles in total, or 500 miles away from the harbor. Therefore, the fishing range of small fishery companies would be a circle centered at Inverness Harbour, with a radius of 500 miles.

5.3 Defining Best, Worst, and Expected Elapsed Time

The plot below generates the possible distribution of both mackerels and Scottish herrings in each year from 1981 to 2070, from which we can observe a clear pattern of northward migration. This helps us define the best and worst elapsed time until both species migrate out of the fishing range of small companies. Specifically, the best elapsed time is when the southern bound of the fish distribution moves out of the fishing range; in this case, as soon as the southern bound is out of the fishing range, fishery companies would be unable to catch the fish. Similarly, the worst case is that we assume the fish occurs at the northern bound of the potential locations, when the northern bound of the fish clusters moves out of the fishing range, fishery companies are unable to harvest any fish. As for the expected case, it is considered as the year when the center of all possible locations is no longer inside the 500-mile range.



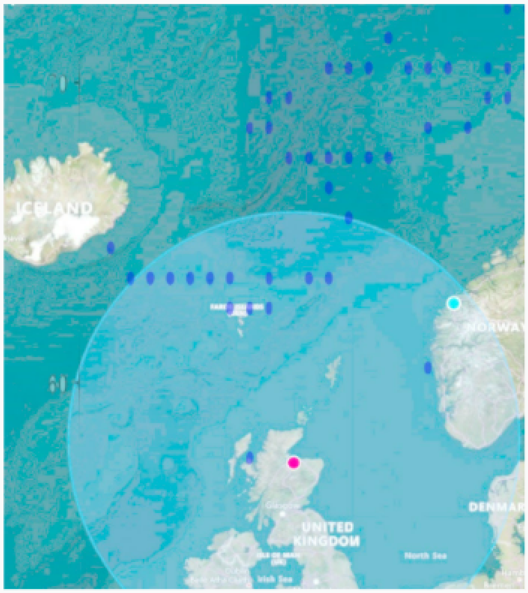
Distribution of Mackerels Across Years



Distribution of Herrings Across Years

Youtube link for the mackerel video: https://youtu.be/mnCoqY1DGYM
Youtube link for the herring video: https://youtu.be/iXpgTCZq1fA

The pictures illustrated below help us to determine if the fish clusters have moved out of the fishing range in a particular year. The circles in both pictures represent the 500-mile fishing range of small fishing vessels, and the dots in blue or red indicate the possible locations of fish in 2070. Although the majority of dots are no longer inside the circle, there are still some dots remaining (these dots are considered as the northern bound of all possible fishing locations); yet, based on the general pattern of northward migration, these points might move out of the range any time. Therefore, some time between 2071 to 2075 might be the best case for elapsed time.



Scottish Herring

Mackerel

5.4 Table of Best, Worst, and Expected Elapsed Time

Based on the assumptions about the fishing range and elapsed time, we obtain a table of the potential elapsed time for both species. Since we only make predictions about fish locations from 1981 to 2070, yet by 2070, the northern bound of the fish clusters have not moved out of the fishing range, so the best elapsed time would only be an estimation rather than an exact time.

Category	Expected Case	Best Case	Worst Case
Mackerel	2060	2070+	1997
Scottish Herring	2045	2070+	2000

5.5 Proposals for Fishing Companies

Based on our prediction, if these small fishery companies in Scotland do not accommodate the changing location of these marine species, there might be a great impact on the fishery industry in Scotland since these small companies comprise a significant portion of the fishery industry. The following proposals provide some insights into how these companies might make adjustments with regard to the fish migrations.

- Improve their equipment: the primary concern of these companies is that their fishing vessels can not support long-range fishing; therefore, by improving their fishing vessels, either changing to larger vessels or equipping their boats with on-board refrigeration, such difficulties might be overcome.
- Collaboration with foreign companies: as the fish clusters keep migrating northward, they will enter the territorial water of other countries, particularly Iceland and Norway. If small companies are able to collaborate with the fishery enterprises in these countries, the cost of long-range fishing can be reduced.
- Build offshore ports: offshore ports are mainly used for import and export transshipment now, if more ports of such kind can be built or existing ones can be applied to fisheries, these small companies can still thrive even when the fish clusters move out of their current fishing range.
- Change in business models: small companies can change their current business model and merge with other companies of similar scales to reduce the cost of equipment refinement.

6. Strengths and Limitations

6.1 Strengths

- Our model is very accurate as we divided the ocean area into 660 small regions with each region of the size 1° in longitude and 1° in latitude. We can precisely locate the migration position of the fish in each year. As a result, the general trend of the location change and the years we suggested that the fishing companies might be unable to reach the fish is also more reliable and close to reality.
- Our model is a good combination of the actual data and the data we predicted; hence, this can also validate our result concluded from the model we built. For the model on the fish migration position, we applied the actual fish distribution for 1981 ~ 2015. Though the distribution of recent years could not be found, we can still validate our model using the dataset.
- Our model includes randomness rather than being deterministic and definite. To show randomness, our temperature model is built upon interval prediction. We also provided the small fishing companies with the best and worst case scenarios.
- Our general mindset, modeling approach, and the model can be easily applied to other species under similar circumstances.
- Both the research idea and the displays of our model are quite readable and concise, so readers can understand the information we are trying to deliver without much effort.

6.2 Limitations

Technical parts:

- **Lack of current data that could be used to do validation.**

  Based on the process of model building, we used the temperature data from 1981 to 2015 with respect to the location of each year to predict the estimated temperature of each year up until 2070 and to see which location has expected temperature within the range of suitable living environment of the two fishes. Although we used the function "predict" in R to build the linear model, we actually lack the data showing Mackerel and herrings' locations for years from the 90s to 2020, which may be able to serve as the validation data set for our linear model. In fact, the default function "predict" in R provides us a confidence Interval from the outer range to the inner range of the temperature at a specific location. However, because even a slight change in temperature will result in a shift in the fishes' migration routes, we could make the prediction interval more compact if we could use the actual location of fish to test the model and even apply more advanced statistical regression techniques such as LOOCV (Leave-One-Out-Cross Validation) to make it more precise. Therefore, it is always necessary and helpful for researchers to conduct more thorough sampling and gather more cleaned data for data mining.

- **Exploration of more flexible models**

  On the other hand, just as is the case in similar hypothetical questions such as the time needed to raise a dinosaur, we could further handle this data shortage by making assumptions and building models with higher flexibility. More advanced techniques such as splines and random forest may help us to decrease the Mean square of error and narrower the CI.

- **Factors that may change over time**

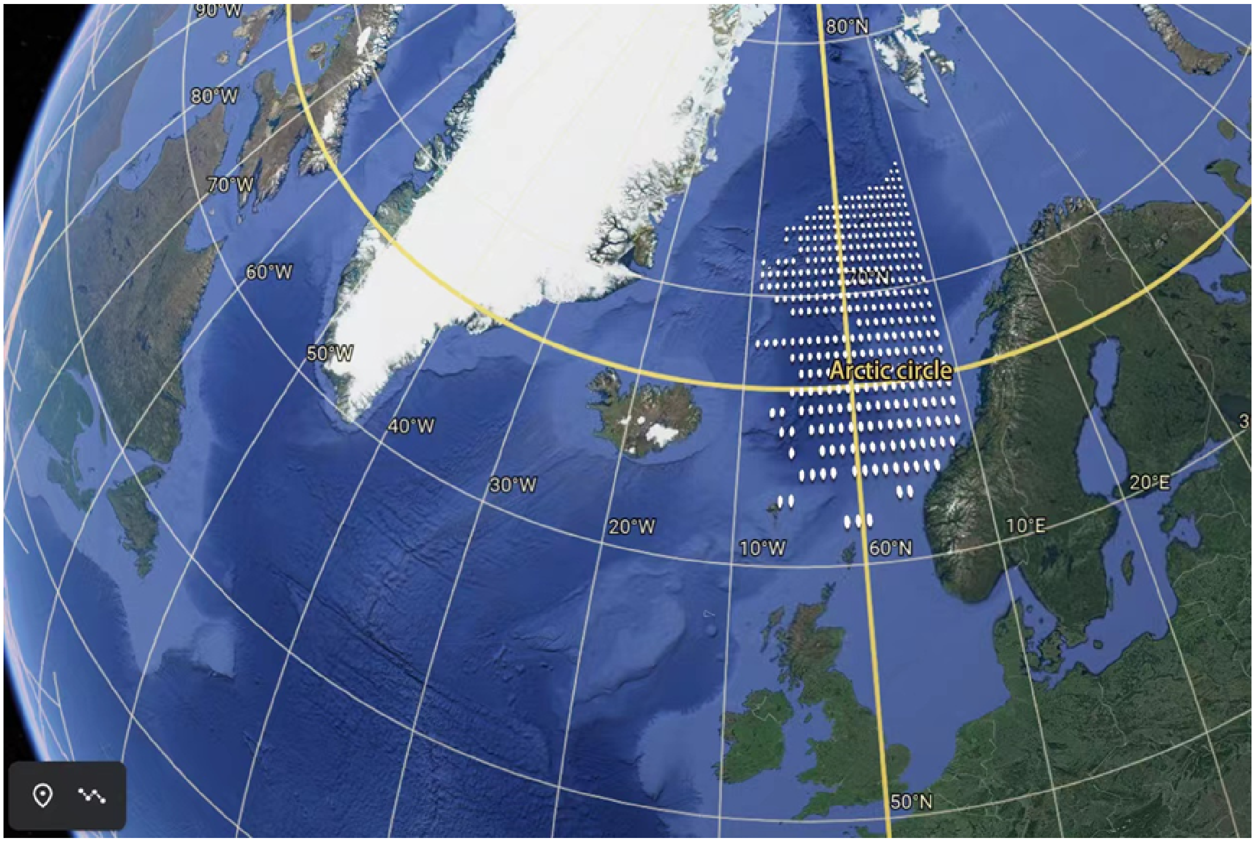
  Preferable temperature is one of the factors that might change. Although the body temperature and the ideal temperature for habitation may not change drastically in the next 50 years, if this study needs to be applied to a larger time frame, adding these potential changes could make the model more reliable.

7. Conclusion and Future Directions

In the context that there will be a northward migration for Atlantic marine species over the next 50 years, we use a temperature prediction model and a fish-migration location model to quantify the change in fish distribution. Using the models we obtained, we conclude that small fishery companies in Scotland need to make adjustments urgently because the fish clusters are highly likely to migrate out of their fishing range by the next few decades.

Our model focuses on mackerels and Scottish herring in the north atlantic ocean, and we assume that the environmental conditions other than temperature and some potential changes that may affect fish migration are neglected, future researches can emphasize on how human activities, environmental catastrophes, and biological changes might make a difference to fish migration. Research can also be expanded to other species or other areas, to see if similar patterns exist or if local businesses need to be more compatible with any upcoming changes. Suggestions on future research are listed below.

- Random stochasticity - unpredictable human activities and environmental catastrophes
    - Technology developments have led to severe pollution, which will undoubtedly affect the ecosystem in general. For example, the potential leakage of nuclear waste can dramatically change the living environment of the ocean. The radiation may also change the genetic materials of marine animals, which could possibly lead to mutations of biological features, for instance, the range of preferable temperature might be different. This is a way of how human behaviors may aggravate the deterioration of the local marine living environment and expedite the migration of fishes, which will lead to the deviation of the actual fish's position.
    - Some environmental issues, such as meteorological abnormalities, could also be blended into the model. For instance, Iceland has many active volcanoes both under the sea and on the mainland. According to Iceland's Institute of Earth Sciences, these volcanoes exhibit an approximately 5 years eruptions circle.A considerable amount of chemical deposit along with the lava will be emitted into the ocean, which will increase the acidity of seawater and even the explosive growth of phytoplankton, which may further affect the speed of fishes' migration. Incorporating these stochastic elements into future studies enables us to take a deeper insight into some practical problems. Similarly, the movement of current may also slightly play a part in determining the route of fishes' migration.
- Other factors that also contribute to fish migration
    - Migration of other species: other species, particularly the predator and prey of our target species (mackerel and herring), might also migrate due to temperature changes. Future studies can focus on how mackerel and herring will migrate if their major food sources such as krills also endure a northward migration.



- Beyond the scope
  - Other Atlantic species: future studies can apply similar models to investigate the movement of other species in the North Atlantic Ocean. Our model focuses on the relationship between temperature and fish movement, and other species may share similar assumptions with our model. Such a relationship between temperature and migration for other species can be inferred based on our current model.
  - Similar migration patterns in other areas: global warming affects the entire ecosystem as a whole, therefore, applying our current model on fish migration in the Atlantic ocean, upcoming research can inquire into how temperature change affects animals in the pacific ocean or even on land.

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