Problem Chosen
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MCM/ICM
Summary Sheet

Team Control Number
2020069

Finding Nemo

Predicting the location of Scottish herring and mackerel after future temperature increases

Team #2020069

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The large scale behavior of fish has always been of interest to scientists due to the significance of fishing industries in many economies, but the increase in global ocean temperature has driven a new wave of interest in the subject. Particularly, the Scottish fishing industry is one of the principle drivers of the Scottish economy and would be put under enormous strain if the fisheries of the North Sea moved out of range for most fisherman.

The mackerel in the North Sea can be divided up into three principle groups depending on where they spawn. One group spawns in the bay of Biscay to the south, another on the western edge of the continental shelf near Ireland, and the final, towards the north end of the North Sea. The question of the distribution of the North Sea spawning mackerel isn't new. During the 1960s the mackerel were observed to winter near where they currently do, around the northern edge of the Norwegian tench. However, during the 1970s, they stopped wintering in the north, and instead wintered in the southern end of the North Sea due to both fishing pressure in the north and a decrease in temperatures. [5] Having since returned to their original wintering habits, it is important to understand what drove that change and how temperature will drive future changes.

We constructed two models to predict the response of mackerel and herring to rising temperatures. Since mackerel and herring have similar prefered temperature, around 10C, we model both fish together. Using a random walk(esque) model to simulate the potential migration of North Sea mackerel during the next 50 years based on the predicted sea surface temperatures (SST), we observed very little change in fish distribution. Using a model to solve for a steady state in the distribution of fish during the four seasons and at predicted surface temperatures for the next fifty years, we found slightly more variability than our random walk models, but still within the range of small Scottish fishing companies.

Contents

1 Background

The prediction of fish position can have a large economic impact on the fishing industry. It is well known that global environment change plays a significant role in marine animal movement. One of the most important environmental factors for fish migration is the sea surface temperature (SST). Studies have shown that fish tend to move to areas that have favorable temperature. Over the past few decades, the global sea temperatures have risen by 0.7 degree, and is expected to keep rising ([2]). The large change in SST makes it possible that fish move to positions that they rarely appear before. Therefore, the prediction of annual fish position, especially for commercial fish location, is more necessary than ever.

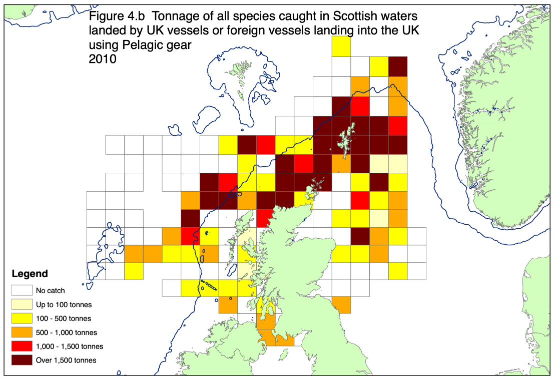

Figure 1: Scottish fishing activity map retrieved from the Scottish Sea Fisheries Statistics website (https://www2.gov.scot/Topics/Statistics/Browse/Agriculture-Fisheries/Distributionmaps)

2 Model Assumptions

Due to the complexity of global environment and animal movement, the following assumptions are made for the model.

- Only the temperature and depth of seas close to Scotland affects the herring and mackerel population.

  The geographical domain concerned in this model includes the North Sea, the Celtic Seas, and part of North Atlantic Ocean, defined by latitude between 50N and 63N, and longitude between 12W and 11E. However, our models assume a projections of the region onto a rectangular domain based on the latitude and longitude coordinates. As such, we do not account for the horizontal distortion caused by the projection, but this distortion likely does not impact the models. The model's aren't based on any absolute measures (such as speed) that would change with latitude.

- The movement fish take only depends on the temperature at the moment. Previous action will not affect the movement of fish

- Herring and mackerel's migration behavior in response to water temperature change has no lag behind climate change.

- Herring and mackerel's biological features stay the same, so that their preferred habitat's temperature and hatching locations do not change over time.

  It is likely that herring and mackerel are adapting to the rising ocean temperatures. However, it is difficult to acquire the data to accurately model their biological evolution over time. Considering the 50 years time span, equivalent to 4 to 5 lifetime of a herring or mackerel, it is also reasonable to assume that no major biological change occur to either fish.

3 Mathematical Model

3.1 Sea Surface Temperature

Since sea surface temperature is the main factor that affect the movement of fish, we want SST, both present and future data, across England and its near sea region. To be specific, we divide the whole England region into grids, and we want the temperature at each single grid. There are plenty of studies and variety of models on the prediction of future sea surface temperature (SST). A thorough simulation of sea surface temperature may require atmosphere model, general circulation model, and a lot more models and parameters based on the sanity of sea, current, air component and so on. However, due to the complexity of predicting weather and the limit of time, we will use the predicted data proposed by [4], and predict the temperature at each position based on the changing rate of annual regional temperature.

3.1.1 Representative Concentration Pathway

Representative Concentration Pathway (RCP) is a green house gas concentration trajectory. Most current works of global temperature prediction takes RCP into account. Popular RCP temperature models are RCP2.6, RCP 4.5, and RCP 8.5. The numbers stands for the level of radiative forcing at year 2100(2.6, 4.5, 6.0, and 8.5 /(W/m2)). The higher the number, the worse the greenhouse effect. The predicted temperature in future 50 years across the north sea area is shown below.

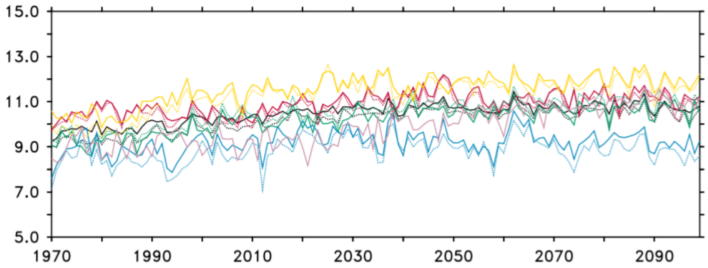

Figure 2: Temperature prediction based on RCP 2.6 model.(Data from [4])

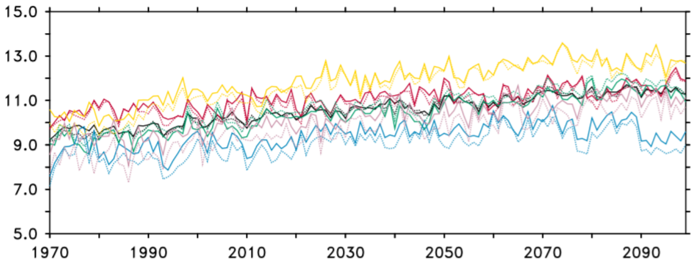

Figure 3: Temperature prediction based on RCP 4.5 model.(Data from [4])

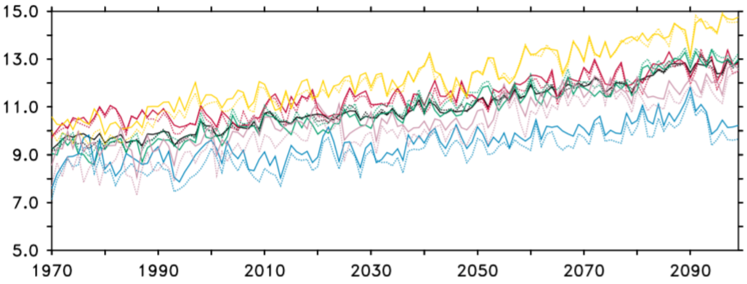

Figure 4: Temperature prediction based on RCP 8.5 model.(Data from [4])

3.2 SST prediction

Based on the temperature increasing rate, we find that at best case, predicted by RCP 2.6 model, the temperature rise by about one C from 1970 to 2100. At worst case, using RCP 8.5, the temperature rise by 4 degree from 1970 to 2100. To predict the future SST, we also need current SST data for every single grid. Current marine data is obtained from NOAA website (https://www.nodc.noaa.gov/cgi-bin/OC5/gin-seas-climate/ginregcl.pl). We select data based on the location of England. The latitude of data we use for analysis ranges from 49.875°N to 64.625°N , and the longitude ranges from 13.625°W to 11.125°E . Using the rate of change of temperature and current temperature, we can give a rough temperature prediction in the next 50 years.

$$T = T(current) + T(prediction) + T(error)$$

T(error) serves as a noise that range from -0.25*T(prediction) to 0.25*T(prediction). We use T(prediction) = 1.5 for our general case, T(prediction) = 5 to be our worst case, and T(prediction) = 0.5 to be our best case.

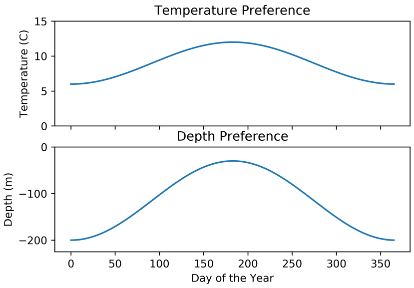

Figure 5: Temperature and depth preferences assigned to fish based upon the time of the year.

3.3 Two Dimensional Random Walk Model

Random walk model is a stochastic process that model the path of a consecutive random movement. An easiest example of random walk is the movement of an object on one-dimensional integer line (x axis). At each position, the object has the possibility to move to left with a possibility $p(x, x+1) = q$, and move to right with a possibility $p(x, x-1) = 1-q$.

We extend this basic concept into two dimensions in order to model the behavior of individual fish in response to environmental conditions. After considering the behavior of fish from the macro to the micro scale, we concluded that they may be modeled by pseudo-random walks. We introduce several factors that influence the probability of a fish to move in any given direction based upon local environmental conditions. Thus, we model the behavior of individual fish in order to observe the behavior of the system as a whole. The problem of modeling the response to temperature change necessitates that temperature influence how the behavior of fish. Furthermore, research suggests [6] that the behavior of pelagic species, including mackerel and herring, during spawning is to proceed to shallower water. As such, another factor of our model is the depth of the sea at a particular location.

3.3.1 Walk Probabilities

Research strongly suggests that pelagic species require specific ranges of temperatures to survive, particularly during spawning at which time the eggs are more vulnerable to dying due to too high or low temperatures. We model this behavior, as can be seen in figure 2, by giving the fish a preference temperature based upon the season. Furthermore, it has been observed [7] that mackerel tend to winter in deeper waters. In the case of North Sea mackerel, this has been observed to be along the edges of the continental shelf and along the Norwegian Trench. In order to reflect the time dependent variations in depth preference we, similar to temperature, introduce a seasonally dependent preference.

Using these preferred temperature in order to guide the fish in their local movements, we calculate a score for a unit vector pointed in any given direction:

$$S(\hat{x}, t) = -\hat{x} \cdot \nabla(|T - PT(t)|) - \hat{x} \cdot \frac{\nabla(|D - PD(t)|)}{25}$$

Where $PT(t)$ and $PD(t)$ are the preferred temperatures and depths as a function of time, and $\hat{x}$ is any unit vector. The negative gradient of the absolute values serve to find the direction of the ideal environmental conditions. By dotting the given unit vectors with these gradients, we get a measure of how much going in a given direction will help reach a more highly preferred environment. The 1/25 factor of the term for depth is present in order to normalize the scales of the two terms and give them equal weight. Since the range of temperatures in our model are 0-15 and the range of depth is 400-0, the factor of 25 makes them equally weighted.

For each of the four cardinal directions we calculate a probability, after making all scores positive, with the following equation:

$$P(\hat{x}) = \frac{S(\hat{x}) - (1 - forcing)(S(\hat{x}) - 0.25)}{\sum_{directions} S(\hat{y}) - (1 - forcing)(S(\hat{y}) - 0.25)}$$

In this manner we introduce a "forcing" term that controls how much of an impact the local conditions have on the behavior of a fish. When forcing equals 1, they will always abide by what will bring them towards the optimum environment. When forcing is 0, they behave without regard to environmental conditions.

We chose the forcing parameter by matching the model's predicted distribution under current conditions and recent observed distributions of fish. However, though the forcing has significant impact on both extremes, the value we ended up using (0.2) is just the middle of a qualitatively correct range, and is therefore not precise. Without more detailed information on current distributions, this can only serve as a reasonable approximation for a more precise forcing term.

We ran the model over one year using historic data and predicted temperatures based on the historic data. We initialized the model to begin the walks off of the Shetlands, approximately where mackerel are observed to winter currently. We use 10,000 walkers, with 5 walks per day, for 365 days per year.

3.3.2 Model Results

Running the model under current conditions (figure 4) we observed considered similarity to the map of catch distributions provided by the Scottish government (figure 1) and to studies of northern mackerel wintering habits [9]. We can see a proclivity towards gathering on the north-western edged of the Norwegian trench (see figure 3) and around the Shetland Islands. During the spring and summer there is a shift towards the south and the warmer waters in the lower part of the North Sea where mackerel have been observed to spawn. However, the model shows a remarkably low sensitivity to increased temperature, predicting qualitatively identical distributions in the current environmental conditions and conditions with a severe five degree Celsius increase.

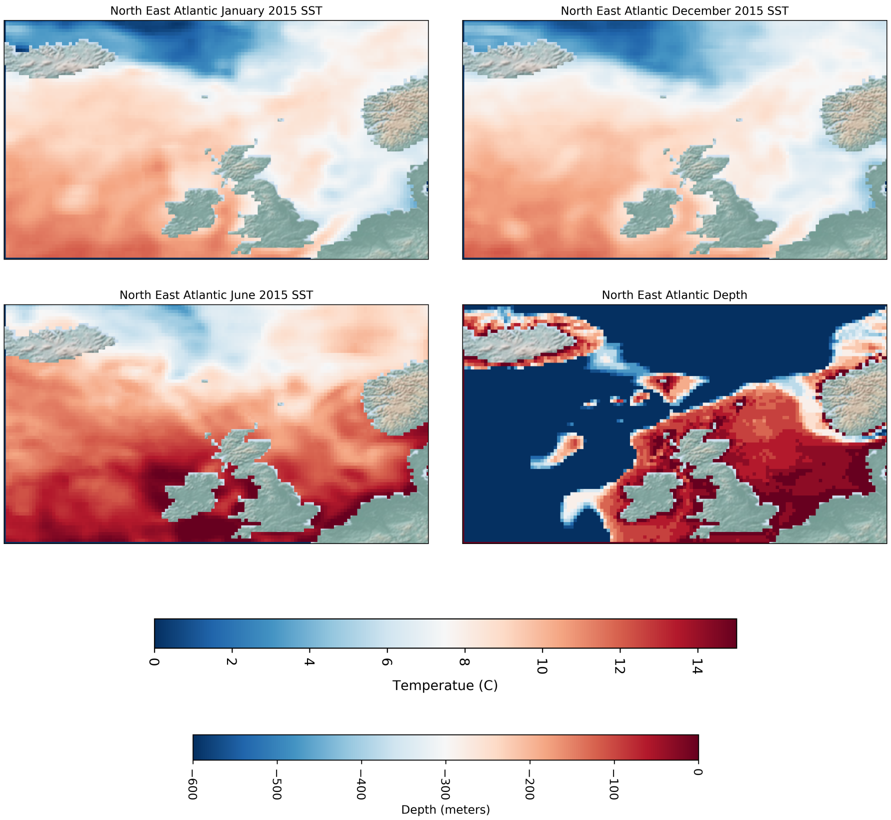

Figure 6: North Sea sea surface temperature (SST) in 2015 and the depths of the North Sea and surrounding water. (Data from [8], [3])

3.3.3 Model Shortcomings

The model bases the behavior of fish off of entirely local environmental conditions. Though there is a non-zero probability of fish going in a non-locally optimal direction, that deviation is not sustained over large distances and is quashed by the gradients. This may not be how fish behave naturally though, as evolution can embed instinctual patterns of movement into fish that do not respond to local conditions. As such, by taking into account the depth that the fish appear to prefer, we may be basing our model off of merely a correlation to the fish's behavior, and not a causation.

One possible example of this downfall can specifically be observed in the winter fish distributions of the model shown in figure 4. According to the model, the mackerel tend to cluster around a point south-east of the Shetlands. Comparing this to the depth map in figure 3, we can see there is a small bowl in the sea floor. In the fall when the fish preference is moved towards deeper water,

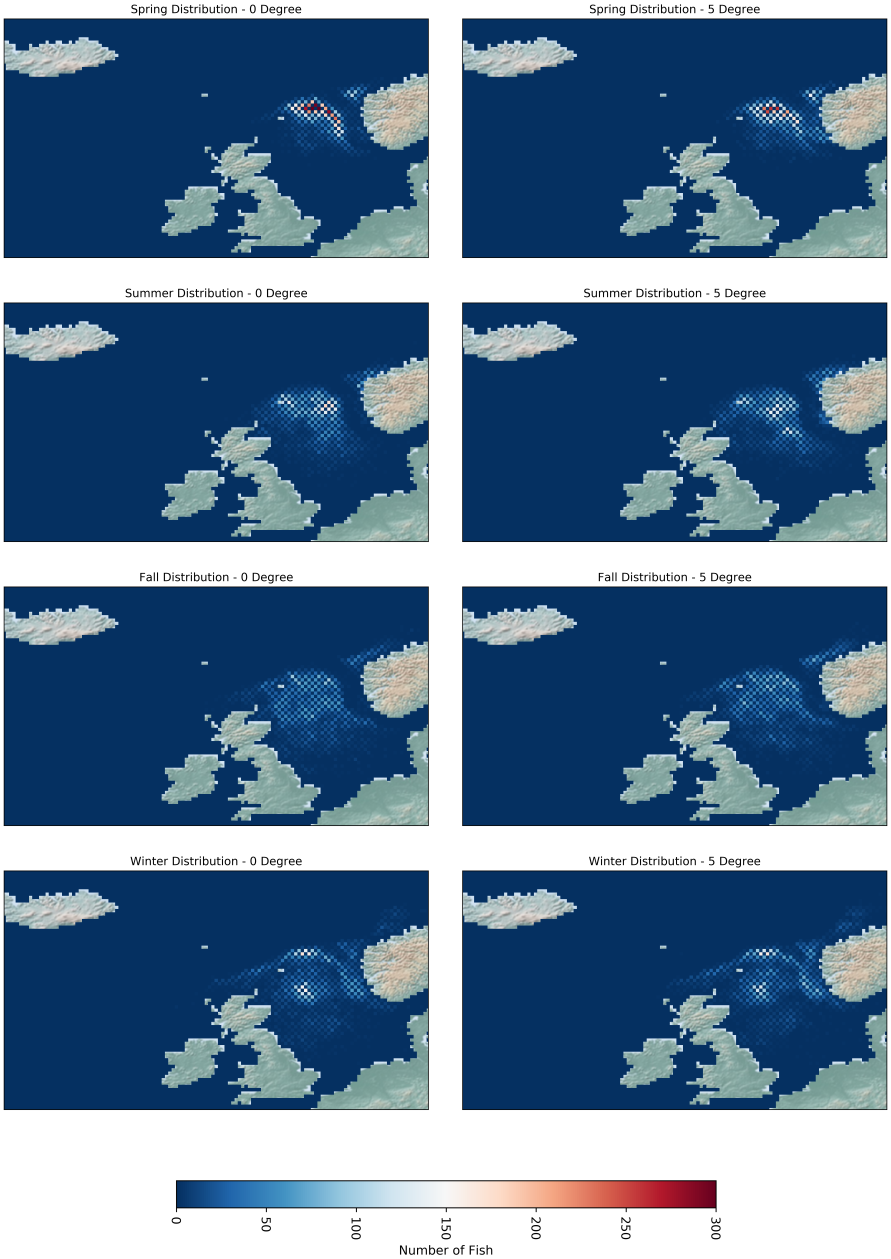

Figure 7: Random walk model's predicted distribution for current temperatures and for temperatures with 5 degree uniform increase.

they become trapped in the bowl as they are only looking at local gradients in depths. In reality, this behavior is most likely not present due to both the fish not being bound to the floor of the sea (as our model assumes) and an ability for fish to follow instinct rather than local conditions alone.

3.4 Steady-state Population Distribution Model–same idea, different implementation

Even though the ocean temperature is changing overtime, at each instance, a steady-state population distribution based on the instantaneous ocean temperature and depth. Based on the assumption that fish population adjust to climate change without lag, the steady-state population distribution is reached at all instances. At steady-state, the population distribution stays the same, meaning that the total population flux in and out of a position are equal. Using this condition, the population distribution can be solved using numerical mesh analysis.

3.4.1 Mesh

A 92 by 59 regular mesh of the spatial domain is carried out to solve for the steady-state distribution. The distance between neighboring nodes is uniformly 0.25 degree in both the latitudinal and longitudinal direction. At each spatial node, the population flux out of a node is equal to the population flux into the node under steady-state condition. Mathematically, the condition at each internal node is expressed as:

$$\sum_{k=1}^{4} X(\hat{x})P_k(\hat{x}) = \sum_{k=1}^{4} X(\hat{x}-\hat{a_k})P_k(\hat{x}-\hat{a_k})$$

$\hat{x} = (i, l)$ is node location.

$\hat{a_1} = (1, 0)$, $\hat{a_2} = (-1, 0)$, $\hat{a_3} = (0, 1)$, $\hat{a_4} = (0, -1)$ are unit vectors pointing to neighboring nodes.

$X(\hat{x})$ is population at location $\hat{x}$.

$P_k(\hat{x})$ is probability of fish migrating from $\hat{x}$ to $\hat{x} + \hat{a_k}$, same as the walking probability in section 3.1.2.

3.4.2 Boundary Conditions

The boundaries of the spatial domain is modeled as infinite barriers that fish are not allowed to cross. Alternatively, modeling equal flux of fish population entering and leaving the spatial domain at each boundary leads to the same mathematical formulation of the boundary condition. The interaction between ocean and land is also modeled as infinite barrier, and fish population in terrestrial regions are forced to zero. These boundary conditions are applied through modification of migration probabilities at the boundaries.

At boundaries, we assume that migration probability in boundary's direction is zero, ensuring the infinite barrier boundary condition. For example, at node (1,1), the south-west corner of the spatial domain,

$$P_2 = P_3 = 0$$

is forced by setting

$$K_2 = damping + forcing_T \frac{-\partial |T - PT|}{\partial x} + \frac{forcing_D}{500} \frac{-\partial |D - PD|}{\partial x} = 0$$

$$K_4 = damping + forcing_T \frac{-\partial |T - PT|}{\partial y} + \frac{forcing_D}{250} \frac{-\partial |D - PD|}{\partial y} = 0$$

$$P_k(1,1) = \frac{K_k}{\sum_{i=1}^{4} K_i} = \frac{K_k}{K_1 + K_3}$$

3.4.3 Parameter Setup

The model reads sea temperature data that varies with year and season, and ocean depth data that remains unchanged in prediction time domain. The model considers both temperature and depth as factors driving fish migrate, and the varying value and importance of the two factors over seasons. Both herring and mackerel seek shallow and warm water regions to reproduce and hatch in the spring, but are not stimulated to migrate to warm or shallow water during other seasons. Based on this information, the model set $forcing_T = forcing_D$, and set favored water temperature as high as 14°C during springs, while setting $forcing_T = 100 forcing_D$ and the favored water temperature as 9.5°C during other seasons of the year.

3.4.4 Solving Steady-state Model

The steady-state population solution at each spatial node is solved by formulating the equations at all 5428 nodes into matrix equation form: AX=b, where A is 5428 by 5428 sparse matrix containing all coefficients, X is a 1 by 5428 vector containing the population at all nodes, b is 1 by 5428 vector containing all the constant terms of the equations. MATLAB is used to solve the matrix equation and to plot the result.

3.4.5 Model Results

The result shows a similar pattern to the previous simulation result in that there is no significant distribution pattern change. The center of the steady-state population distribution in winter moves north from near 50°N and 52°N to near 60°N in the next 50 years. However, the region with large population fraction shows no significant change. This means that fishing companies are unlikely to see their nearby region deplete of herring and mackerel population, but likely to see decline in the fish population for southern locations, and increase in fish population in northern locations along the west coast and north coast of Scotland.

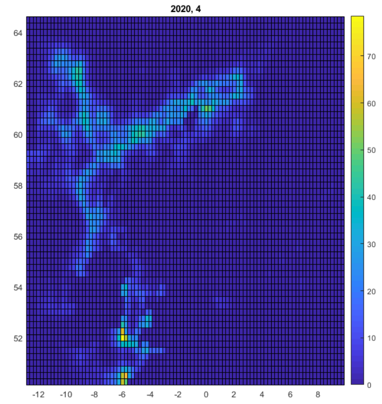

Figure 8: Predicted Herring distribution, winter 2020

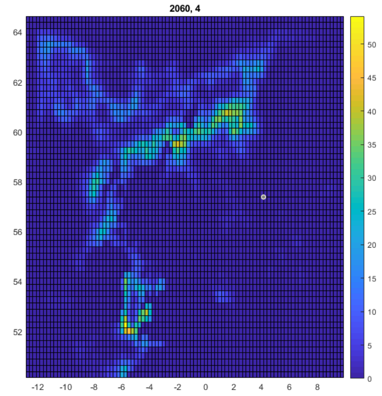

Figure 9: Predicted Herring distribution, winter 2060

The result of the model also shows significant seasonal variation in preferred habitat location, especially for spring season due to changed parameter settings for spring. The model predicts that herring population to be centered in the southern region North Sea and southern Irish water in spring, as shown in Figure 10 and Figure 11. The distribution resembles the actual distribution of newly hatched herring and mackerel distribution provided by the Scottish government [1]. The result shows that the center of population distribution for herring and mackerel in spring .

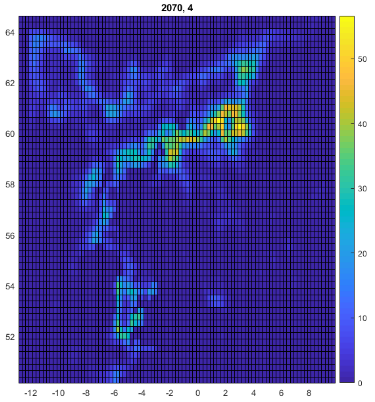

Figure 10: Predicted Herring distribution, winter 2070

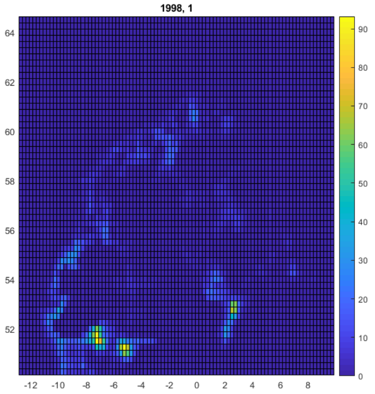

Figure 11: Predicted Mackerel distribution, spring 1998

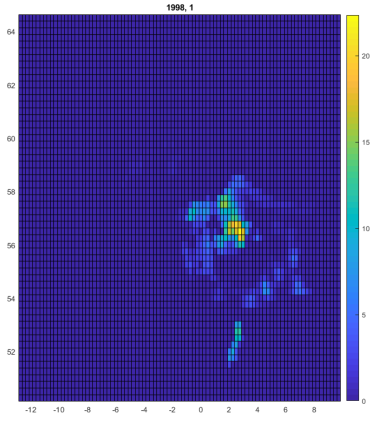

Figure 12: Predicted Herring distribution, spring 1998

4 Conclusions

Both Random Walk model and Steady state model show visible northern migration of the center of population distribution of mackerel and herring over their center of population distribution, but little change in regions that are habitable to the two species. As such, based on our models, we would predict moderate impact on the economies of Scottish fisherman in the future 50 years. However, both models does show a moving north pattern. It can be clearly seen that fish distribution tends to move north.Therefore, further future, it is expected that both herring and mackerel move to a place far from Scotland.

5 Future work

The temperature of our model can be more accurate. In this paper, we use temperature data mainly from the predicted annual data and current SST data. More precise predicted data output can be obtained through CMIP 5. There are plenty of monthly data that can be used to enhance the data precision.

Aside from obtaining data, both of our models focused on two primary factors effecting the fish's behavior: temperature and depth. Though these are certainly factors, they may not be the most important such factors that we could consider. Doubtless, fish have some instinct that drives them towards certain actions, instinct which, though we may not know exactly, we may be able to approximate from observational evidence. Though we were not able to incorporate this into our current model, it may cause significant shifts in the ultimate distribution of the fish.

Furthermore, the temperature data used in our models is sea surface temperature, which is not representative of the temperature where the fish may actually be below the surface. The lack of consideration for temperatures at depth, combined with assuming the fish to be at the maximum depth of the sea floor, could play a significant factor in the outcome of the model. We could allow three dimensional freedom of movement by not including a depth gradient term unless they are at or near the maximum depth.

6 References

References

[1] González-Irusta Aires and Watret Gislason. "Updating Fisheries Sensitivity Maps In British Waters". In: *Scottish Marine and Freshwater Science* 5.10 (2014), pp. 34–41.

[2] Martin J. Genner; Jennifer J. Freer and Louise A. Rutterford. "Future of the Sea: Biological Responses to Ocean Warming". In: (August,2017).

[3] Compilation Group GEBCO. *GEBCO 2019 Grid (doi:10.5285/836f016a-33be-6ddc-e053-6c86abc0788e).*

[4] Christian Dieterich; Shiyu Wang; Semjon Schimanke; Matthias Gröger; Birgit Klein; Robinson Hordoir; Patrick Samuelsson; Ye Liu; Lars Axell; Anders Höglund and H. E. Markus Meier. "Surface Heat Budget over the North Sea in Climate Change Simulations". In: *Atmosphere* 10.1 (2019), p. 272.

[5] Teunis Jansen. "Pseudocollapse and rebuilding of North Sea mackerel (Scomber scombrus)". In: *ICES Journal of Marine Science* 71.2 (Sept. 2013), pp. 299–307. ISSN: 1054-3139. DOI: `10.1093/icesjms/fst148`. eprint: `https://academic.oup.com/icesjms/article-pdf/71/2/299/30383866/fst148.pdf`. URL: `https://doi.org/10.1093/icesjms/fst148`.

[6] Teunis Jansen and Henrik Gislason. "Temperature affects the timing of spawning and migration of North Sea mackerel". In: *Continental Shelf Research* 31.1 (2011), pp. 64–72.

[7] *Mackerel*. `https://www.ices.dk/explore-us/projects/EU-RFP/EU\%20Repository/ICES\%20FIshMap/ICES\%20FishMap\%20species\%20factsheet-mackerel.pdf`.

[8] "NOAA/OAR/ESRL PSD Boulder Colorado NOAA". *NOAA High Resolution SST Data*. `https://www.esrl.noaa.gov/psd/`.

[9] DG Reid, M Walsh, and WR Turrell. "Hydrography and mackerel distribution on the shelf edge west of the Norwegian deeps". In: *Fisheries Research* 50.1-2 (2001), pp. 141–150.