Problem Chosen	2020 MCM/ICM Summary Sheet	Team Control Number
A		2020232

Based on the physics-inspired biodynamics and a cellular automata model, this paper explores the impact of ocean warming on Scottish fishery industry. By regressing on the marine temperature record from 1891-2015, we estimate three trend for the ocean temperature in the future, one optimistic , one pessimistic, and the other one in the middle. The resulting simulation varies between different estimates. Then we establish the potential function field on the ocean surface and give the fish's law of motion in analogy to the motion of charged particles in the electric potential field. Next, we implement the simulations and obtain the distribution of herring and mackerel over time. Finally, we analyze the economic impact of the migration and propose solutions based on the results. We now summarize our answers to the questions as the following:

First, if the temperature rise is at least of medium scale, both the herrings and mackerels will migrate to Føroyar islands. However, if the warming up is mild, the two species might concentrate in the Shetland Island and the north British coast.

Second, as the fish move northward, they will become too distant for profitable landing by 2054 in the worst case. Even under the medium warming up trend, the business will cease to make profit by the 2060s. However, from now till then, there might be a transitional landing boom because the migrating population might linger in the east and north Scottish cost for a while. And if the temperature cease to increase significantly, they may even permanently habit there, bringing constant income to the local fishermen.

Third, if the temperature rise is more than mild, we suggest merging the Fraserburgh center, which is the one of the industry's headquarters in the south, to the north headquarter Peterhead because its closer to the flocks. The small companies can also merge into large corporations in pursuit for the scale economy of the fishery industry. They can share the fixed cost of an offshore fishing platform and diffuse the risk of distant voyages, which helps them to save the insurance bill.

Last but not least, since the fish will swim out of Scottish Economic Zone into the Føroyar islands, Scottish government should take actions to keep or re-establish a multi-lateral contract over the quota and regulation of the landing activity in nearby waters. It could resort to official cooperation and if possible, invest in the Føroyar islands and encourage international fishery companies to run business with the Føroyar islands' local residents. But on account of the potential negotiation cost, the decline of the industry might be even earlier. The government had better come up with an alternative industry for the future.

Key words: Ocean warming, biodynamics model, cellular automata

Ocean Warming, Fish Migration and Fishery Strategy

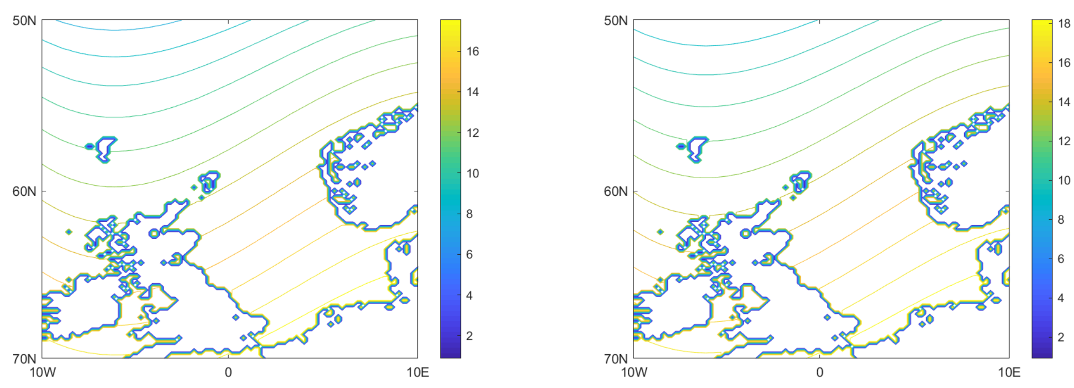
Based on Physics-inspired Biodynamics Model and Cellular Automata

1 Introduction

In recent years, more and more scientific research shows that global warming up has been driving animals in the middle latitudes to migrate northward for cool habitats. For example, robin and barn owl, which usually thrive in the south, was reported to show up in Arctic recently. Such migrations have significant influence on the ecosystem. The leaving of orange-breasted wood warbler has led to a serious caterpillar threat to the US forests. Beyond that, the structural change in the distribution of economic species caused by global warming will greatly impact the local economy, especially the people who earn a living in related industries.

Such is the situation that the Scottish people are facing. Every year, Scottish vessels land millions of tones of herrings and mackerels from the North Sea. However, these two pivotal species are likely to set off north for cooler waters. If that happens, Scottish fishery industry will be heavily crippled. And as we will show, if the temperature of the North sea increases by 5°C in 50 years, a living by landing herring and mackerel might end up a history.

The ocean plays an pivotal rule in preventing the earth from warming up. However, the warming up of the ocean itself seems to be faster than expected. Scientists warn that people should prepared for a worse situation. Given the situation, it's important to have a deeper look into the development of global warming and animal migration under different potential trends of ocean warming.



(a) 2020 Summer Temperature

(b) 2070 Summer Temperature

Figure 1: The Evolution of North Sea Climate: Summer Temperature Under Medium Warming Up.

This paper is aimed to answer the following questions. What is the trend of ocean temperature in the coming decades? What are the migration behaviors of herring and mackerel under this trend of ocean temperature change? What impact will these migrations have on fisheries in mid-high latitudes, such as Scotland? How to assess these impacts, and what countermeasures should the local fisheries take?

First, with the existing ocean temperature data, we established a model to give three possible trends in the ocean temperature in the next 50 years: high, medium and low. Secondly, we use a **physics-inspired biodynamics model** to give the rules of fish migration, then according to the above predictions of ocean temperature, we establish a model to simulate fish migration in seas near Scotland, which is based on the cellular automaton model and the Monte-Carlo algorithm. Finally, we established a corresponding economic model based on changes in fish distribution, and analyze the impact of fish migration on fisheries.

We implemented the above models in MATLAB and obtained sufficient data. We obtained the *center* positions and relative numbers of herring and mackerel in seas near Scotland under three ocean temperature trends, and analyzed the sensitivity. We obtained forecasts trends for the costs and revenues of Scottish fisheries, and gave a feasible future development strategy for Scottish fisheries.

It turns out that our model is reliable. Then we came to a conclusion consistent with common sense.

Table 1: Notation

Symbol	Meaning
$fish(k)$	the fish flock ranked k
$fish(k).position$	the position of $fish(k)$
$fish(k).velocity$	the velocity of $fish(k)$
q	the *charge* of a fish flock(in physics-inspired bio-dynamic model)
s	the surviving rate of the new fish
m	the *mass* of a fish flock
$\vec{F}$	the *driving force*
$\vec{e}_1$	x-direction unit vector
$\vec{e}_2$	y-direction unit vector
$\Phi(i, j)$	potential function on cell (i, j)
n_f	current number of flocks
n_v	number of voyages made within one fishing season
L	The maximum distance of voyages within one fishing season
I	Fishery income
R	Fishery revenue
$C(C^{dep})$	cost (depreciation cost)

1.1 General Assumptions

▲No significant climate change in the coming decades;

▲At the current stage, herring and mackerel are in an ecological balance with the environment;

▲Food sources of herring and mackerel remain stable;

▲The number of natural enemies of herring and mackerel won't increase or decrease on a large scale;

▲All fish flocks obey the same migration law;

▲Ignore changes in fish sex ratios and their impact on reproduction.

2 Ocean Warming: Three Forecasts

Ocean warming has significant influence on Scottish fishery industry. If the temperature keeps surging, the warm water will eventually prevent the larva of mackerel and herring from maturing. By then, the population will shrink exponentially and within years, herrings will disappear from European continental coast. Therefore, the estimate of the long run trend of ocean temperature is crucial to the accuracy of our model and its implied consequence.

It's notoriously hard to draw a sound forecast. No one can tell whether the recent surge in global ocean temperature is the evidence of a long run surging trend or simply part of the periodical fluctuation. However, recent evidence is in favor of a surge in the long run. *Nature* warns that we have underestimated 65% of the heat that the ocean absorbed from 1990s. And recently, Prof. Laure Resplandy reports that a sea with a depth of 30 feet will be 6.5°C warmer in ten years, much higher than the previous estimate of 4°C. The news is very striking given that 30 feet is just about the average depth of Scottish coastal water. Imagine what will be the consequence if the temperature goes beyond Atlantic herring's viability In just 2040, even in the winter. Even if we adjust the speed with the average ocean depth on a proportional basis, it's still at least 1°C per decade. Then in 2070, the temperature of summer water will reach 25°C, which will render the whole Danmark bay lifeless. The herrings and mackerels will never show up in the entire southern North Sea. The whole fishing industry will be shut down and the economy will be seriously crippled.

Should Scottish people worry about the future? Not necessarily. Though the water near Scottish coast was 1°C warmer in 2000 than 1980, the recent decade only witnessed a slight rise of about 0.3°C in ocean temperature. In Millport and Peterhead, the recent warming doesn't seem to be more pronounced than the fluctuations in the history. Though the Scottish has paid public attention to this issue, the issue seems to be less serious in Scotland than what's stressed on the international conferences, given that the Scottish statistics only shows a mild warming up of $0.2 - 0.4$°C per decade.

Given the disputation over the future warming process, our estimate is not aimed at providing an exact trend. Instead, we provide three estimates that respectively represent a serious, medium and mild warming up. The most radical estimate is related to the belief that the growth will be persistent with a constant rate. In stead of exponential, we only use a cubic polynomial as a fine approximation.

$$T_{it} = \beta_0 + S_1(t) + S_2(Latitude_i) + S_3(Longitude_i) + \epsilon_{it} \tag{1}$$

where $S(x)$ are cubic polynomial smoothers. The medium estimate is a linear regression in the form

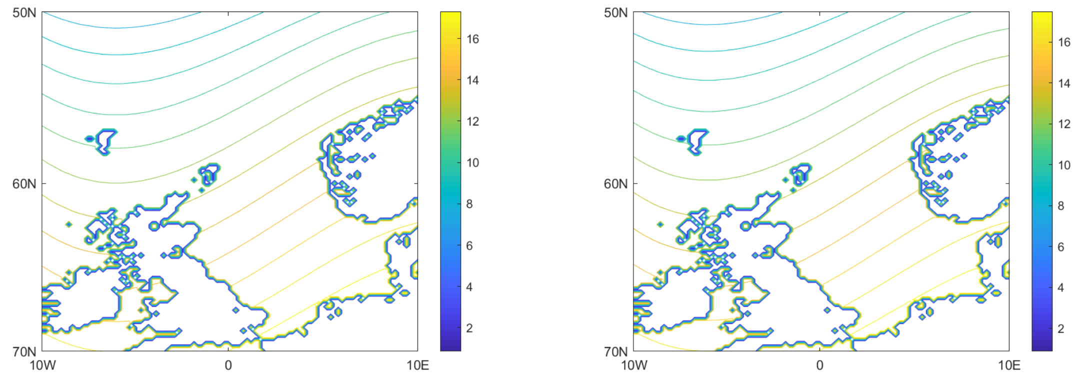
$$T_{it} = \beta_0 + \beta_1 t + S_2(Latitude_i) + S_3(Longitude_i) + \epsilon_{it} \tag{2}$$

and the conservative estimate is based on the belief that the growth rate of temperature will revert to zero in the future. Besides, the current surge in temperature indicates that we are in a middle point of a logistic curve. But instead of implementing the logit regression, we choose the year that has the earlist record as an ad hoc "middle point" t^*. Then We take $\log(t - t^*)$ into the regression which gives:

$$T_{it} = \beta_0 + \beta_1 \log(t - t^*) + S_2(Latitude_i) + S_3(Longitude_i) + \epsilon_{it} \tag{3}$$

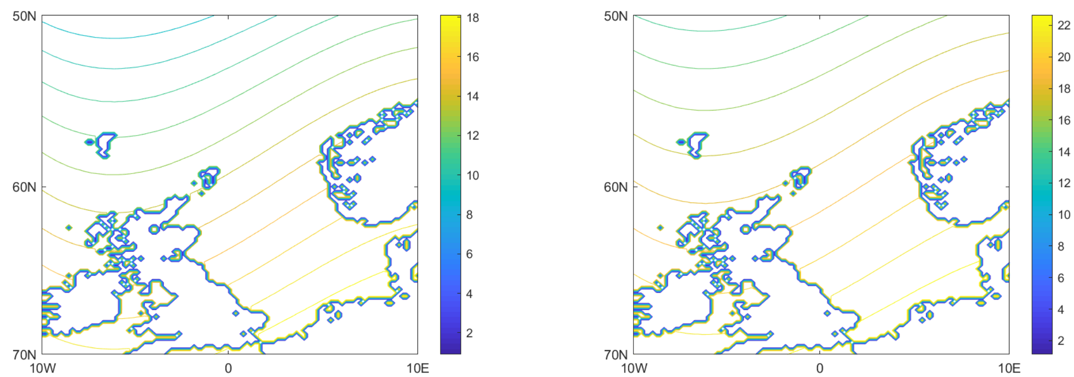
The above T's are all summer time temperature. The reason we choose to use only the highest temperature is that it's the determinant factor. Though the winter temperature will be safe for the fish even under extreme estimate, but we only care if it's there in the summer because we mainly focus on the economic importance and the fishing period is in the warmer half of the year.

Our data is from ICES Oceanographic Data. It provides a consistent historic record of the temperature, salinity and other features of nearly every bite of European ocean. Though there could be only several observations for each station, that's enough to construct a long run warming trend in the geographical magnitude we consider.



(a) 2020 temperature: low

(b) 2020 temperature: low



(c) 2020 temperature: high

(d) 2070 temperature: high

Figure 2: The Evolution of North Sea Climate: Summer Temperature.

As fig:temp.evolve shows[1], the highest estimate is in line with the recent stressful figures, while the mild estimate is consistent with the speed reported in the Scottish government document. In our highest estimate, water temperature in the southeastern North Sea, located in 53°N, 5°E, will be 23.44°C in the hottest August. Meanwhile in the conservative estimate, the water temperature in the same location will be only 18.98°C, only 1 degree higher than the 2017 temperature 17.8°C.

Such divergence will lead to substantially different futures to the Scottish Fishery industry. If the temperature rises by 5.5°C in the half of century, no herring or mackerel can survive the summer heat in

[1]The colorbar of the last plot has a higher upper bound

most parts of the North Sea. The best plan for now is to gradually move the center of the industry to the northeastern corner of British coast where populations of these pelagic fishes still remain, meanwhile to come up with alternative industries to reform the structure of the economy. But if the rise is only 1.2°C, there will be more solutions to the problems caused by the warming up process.

These models are not perfect. For example, the growth in different regions is parallel. But we don't care about more geographical details except that generally, the place with lower current temperature will be more attractive to herrings in the future. Thus a universal temperature rise is a reasonable approximation and enough to drive the fish to migrate.

3 The Fish Migration Model and Simulation

3.1 Design of Cellular Automata

Cellular Automata (CA) is an effective method for simulating animal migrations. In a CA, time and space are divided into small discrete units. This process significantly reduce the complexity of our simulation and introduce an expedient randomness. The evolution of each cell is determined by the status of both itself and its neighbors. Therefore the CA is an efficient tool in simulate how species evolve given the change in the surroundings. In general, a CA model captures two important features of the reality, the randomness of the wild world and the interaction between the animal and the ecosystem. Thus it's a fairly suitable approach to our problem.

We build our model in analogy to physics theory. This idea is partly inspired by the bird migration model in [3]. In our model, we divide the area from 50°N to 70°N and 10°W to 10°E into 100×100 cells. We trivialize the fact that Latitude line becomes shorter as we go North. Each cell is initialized with '0', which stands for the land, and '1' standing for the ocean. Instead of the species density of each cell, we keep track of each flock after its birth (or initialization). This is similar to the idea of tracing the movement of a certain mass element in hydromechanics, which helps us focus on the fish's most informative dynamics. A fish flock is considered to be a particle taking up a cell. The particle's trajectory stands for the trace of migration. We allow one cell to accommodate multiple flocks. For each period, we let the fish move to a new cell or stay still according to the "field" cast by the environment and get a new distribution.

We equip the fish with informative properties like its mass and age, and many realistic behaviors (functions) such as the birth, death and some subtle interactions to the ecosystem. For example, we denote the fish flock ranked k as $fish\,(k)$. It's major properties include:

$$fish\,(k)\,.position = [x, y] \tag{4}$$

which refers to its current position, and

$$fish\,(k)\,.lifespan = U(3, 5) \tag{5}$$

which is uniformly distributed from 3-5 years, in line with the reality, as well as

$$fish\,(k)\,.velocity = [v_1, v_2] \tag{6}$$

which describes the velocity of migration, reflecting the driving force of the field. We discuss the properties and function with more details in the following sections.

3.2 Biology

In this model, we focus on two kinds of fishes: herrings and mackerels. Herrings usually live in the $0 \sim 200$m ocean surface with a temperature between 0.5°C to 11.2°C with the mean 6.6°C. And its larva will never grow mature if the temperature is over 19°C. Mackerels, also called Scomber scombrus, live in waters from 7°C to 17.5°C with an average of 10.2°C. They live in offshore area with a depth less than 500m and won't spawn where water temperature is higher than 21°C[2]. Therefore, we'll take temperature and depth as two major environmental factors in constructing our field.

We define the fish's "viability" or "fitness" as a function of temperature $V(T)$. For herrings, we Let

$$V(6.6) = 1 \tag{7}$$

to simulate a high fitness under the right temperature and let

$$V(0.5) = V(11.2) = 0 \tag{8}$$

These three points determine a unique parabolic function

$$V(t) = at^2 + bt + g \tag{9}$$

where t stands for temperature, a, b and g are fitted parameters. As for mackerels, we estimate a different viability function by changing the three sample temperature to $10.2, 7, 17.5$.

For the sake of concision, we will only take herrings to illustrate our modeling approach. In section 4.1.3 and 4.1.4 we'll respectively consider the mechanism of which the depth and temperature influence the two fishes.

3.3 Fish Migration: An Analogy to Electrodynamics

When considering migration model, a simplest idea is to consider that the fish will always migrate to places where its viability is the highest. However, the behavior of a flock is affected by randomness and the short run fluctuation of environment. Moreover, the perception capacity of the fish is limited, which means it can only take action based on the information nearby. Thus we choose to endow out fish with "limited rationality", i.e. it can only perceive the field in no farther than three units.

In our opinion, the driving force of the environment to species' migration is just like gravity to a real object, or the magnetic field to a needle. We can use formulas similar to *Newton's Second Law* to simulate the motion of the fish. We suppose the temperature field in the ocean has some kind of driving force on fish flocks, which causes them to migrate. To do this quantitatively, we define a potential function $\Phi(i, j)$ on cell (i, j), so the repelling force $\overrightarrow{F}$ on cell (i, j) can be calculated as the gradient of the potential field, which can be written as

$$\overrightarrow{F} = q\left[\Phi(i+1, j) - \Phi(i, j)\right]\overrightarrow{e_1} + q\left[\Phi(i, j+1) - \Phi(i, j)\right]\overrightarrow{e_2} \tag{10}$$

where q is a scaling factor in analogous to the quantity of electric charge in electromagnetism. So we can directly analogize from physical laws to observe the migration of fish. Here since the fish won't

[2]Data source: https://www.fishbase.in/search.php

migrate a long distance within one year, $\overrightarrow{F}$ can be seen as a constant force in each period. Let the width of a cell be *unit 1*. according to physical rules, we have

$$vt + \frac{1}{2}at^2 = 1 \tag{11}$$

where v is the velocity of the fish flock, and

$$a = \frac{F}{m} \tag{12}$$

where m is the "mass" of the fish flock, namely $fish\,(k)\,.mass$. In our model, a fish flock moves one unit after time t. The problem of t not being a integer can be easily solved by rounding. In the meantime, we introduce randomness into our model by assuming that the flock moves according to the principle above with a probability of p, and otherwise moves randomly to one of the four cells beside.

Now we formalize the concrete form of the potential function. We suppose

$$\Phi\,(i, j) = -\sum_{(m,n)\neq(i,j)} \frac{C\,(i, j)}{r} \tag{13}$$

where $C\,(i, j)$ can be given as $V\,(i, j)$, namely the "viability" calculated given the water temperature of cell (i, j) in, and

$$r = \sqrt{(m-i)^2 + (n-j)^2} \tag{14}$$

representing the distance between cells. The minus on the right side of the equation means that the force between cells is attractive force. We think that the potential function given by 13 can reasonably reflect the migration of fish for the reasons below. First, cells with higher fitness have higher $C\,(i, j)$'s, meaning that the attraction is stronger. Second, the distance in the denominator indicates that the attraction becomes weaker as the distance become longer. Finally, the form of 13 is quite similar to that of electric fields, the origin of our model.

Then we describe the law of motion. If we take the influence of depth into consideration, $C\,(i, j)$ should be

$$C\,(i, j) = V\,(t) - \max\{h(i, j)/200, 1\} \tag{15}$$

where $h\,(i, j)$ represents the depth of the sea in cell (i, j), and t represents the temperature. More details such as the resources limitation and competition will be introduced into the field in later chapters.

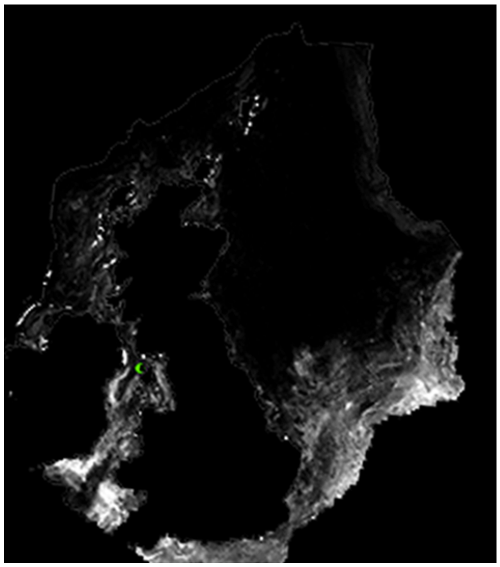
3.4 Birth and Death

We set a lifespan for each fish flock in the model. When a fish's age exceeds its lifespan , it will be removed from the map.

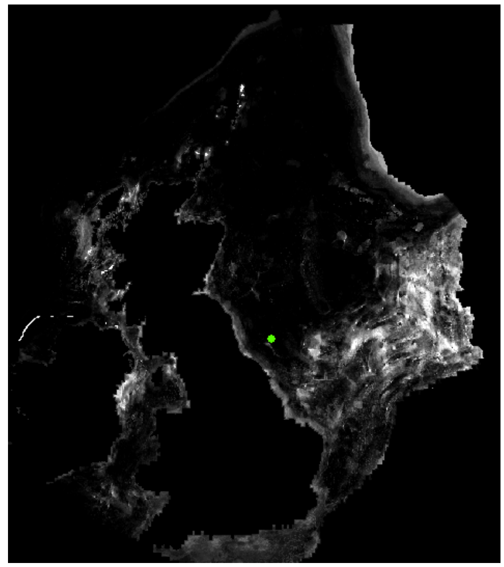
The birth of fish is more complicated. First, we need to generate an initial distribution of the flocks. We use the official record of herring and mackerel distribution to compute the probability that a flock appears in a certain cell [3]. We simply let the probability to be proportional to the average brightness within the area. Based on that, we further consider that the flocks are more likely to appear in their spawning grounds. We rasterize the map of spawning grounds found in [**scottishseafisherystats**] and

[3]Data source: https://data.marine.gov.scot/dataset/updating-fisheries-sensitivity-maps-british-waters

overlap it with the previous probability map. As 3 shows, multitudes of mackerels and herrings are most likely to appear in the continental coast of the North sea and the British western coast in the past decades. As we'll show in our simulation, such distribution will be significantly changed if the summer heat becomes more serious in the North Sea.

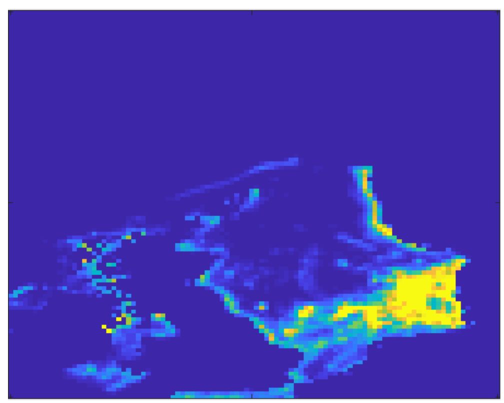


(a) Distribution of Mackerel



(b) Distribution of Herring

(c) Distribution of Spawning Ground



(d) Prior probability of finding Herrings

Figure 3: A Prior Distribution of the Fish

Once the initialization is implemented, the prior distribution's mission is completed. We assume that if the temperature is not as high as to kill the larva, the population will be in a steady state. Thus the dead rate, including human landing, is equal to the birth rate. We implement this feature by assuming that the new generation is always born after the death of the existing generation. And as an unsubstantial simplification, we assume that the whole flock die out simultaneously, leaving their progeny nearby. Again, we can think of the whole flock being landed. The new generation will be born half way between the old generation's birth death location plus a random drift conforming a uniform distribution of $U(-2, 2)$ in each axis, which represents a breeding migration or the attraction of previous habitation. The random drift can be imputed to the currents. But it also serves an important technical purpose. It prevent the flocks from being trapped by bay areas in the eastern British coast. With the random factor, crossing the Shetland strait is much less difficult.

However, if the fish is born in warm waters, it must survive its larva period. We add an ad hoc surviving rate given by:

$$s_{i,j,t} = \frac{1}{1 + \max(\bar{T}, T_{i,j,t}) - \bar{T}} \left(\frac{2}{1 + e^{-0.1(50-n_t)}} \right) \tag{16}$$

where n_t is the current number of flocks. the first term represent the larva killed by the heat, the second term represent the fish's capacity of population recovery. With the surviving rate, we can capture the quantitative effect of ocean warming in a more robust way.

3.5 Supplementary Features

3.5.1 No Fish Ashore

We assume that when a fish flock $fish(k)$ is close to land, the fish flock will "bounce". More accurately, if there is one cell size away from the coastline, using v and v' as the velocity vectors before and after the fish 'bounce', then

$$v' = -v \tag{17}$$

The position of the school remains the same. This will ensure that the fish is always in the ocean.

3.5.2 Limited Resources and Competitive Repulsion

We have not yet considered the interactions between fish groups. A cell's environmental carrying capacity is limited. Given that the resources are limited, multiple flocks will compete for habitats and curb the growth of each other. We add an item to the potential function 13 to represent the "repulsion" between fish flocks:

$$\Phi(i, j) = -\sum_{(m,n)\neq(i,j)} \frac{C(i, j)}{r} + \lambda \sum_{k} \frac{fish(k)}{r} \tag{18}$$

where $fish(k).position = [x, y]$ and $l = \sqrt{(x-i)^2 + (y-j)^2}$ represents the distance between the cell and $fish(k)$. Similarly, we assume that its effect on the potential function is inversely proportional. The "+" sign in the middle means exclusion. λ is a scale factor set to be $\lambda = 0.01$ so that the effect is only not dominant.

3.6 Implementation and Results

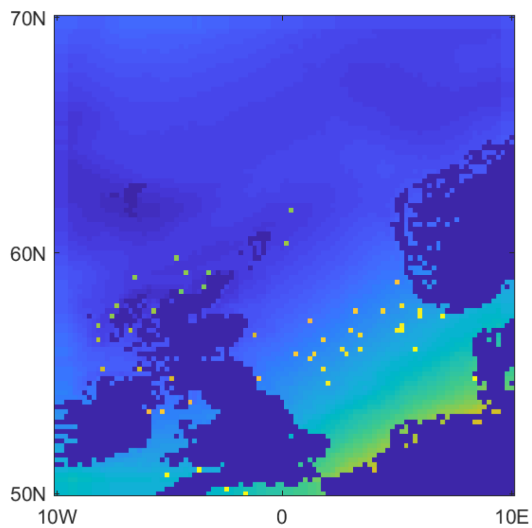
We implement our model using MATLAB. For each year, we first get the temperature distribution and compute the field map. Then we remove the dead fish and give birth to the new generation based on the surviving rate 16. Finally we update their positions and get the information we want to draw from the distribution. We set the scaling factor

$$q = 20 \tag{19}$$

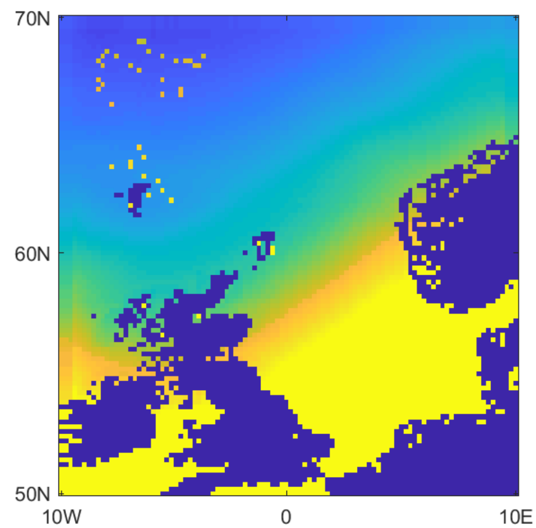
Take herrings for example, Figure 4 shows that given an extreme warming up trend, the flocks migrate a long distance toward north. Summer heat will gradually eliminate all the larva, and in just

50 years, this once populated pelagic fish vanishes in the North Sea totally. They swim cross the trait, far beyond the Føroyar islands towards the pole. It will be more proper to call them Arctic instead of Atlantic Herrings.

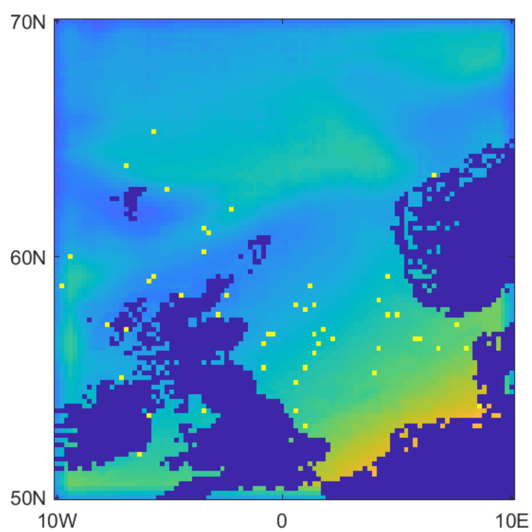
But if we're over-estimating the temperature growth, then things can be very different. The most athletic fish migrate to as farthest as slightly northern to the Føroyar islands, while multitudes of flocks still linger around the Shetland Island in the north Scottish coast. The result shows that a rising temperature is powerful enough to drive the Atlantic herrings to migrate.



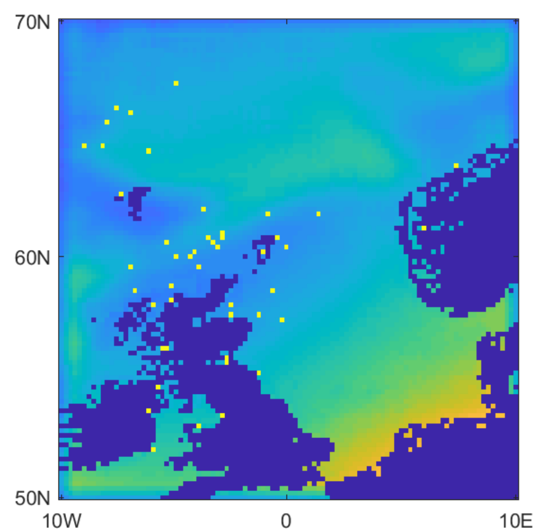
(a) Distribution of Herring in 2020: High



(b) Distribution of Herring in 2070: High



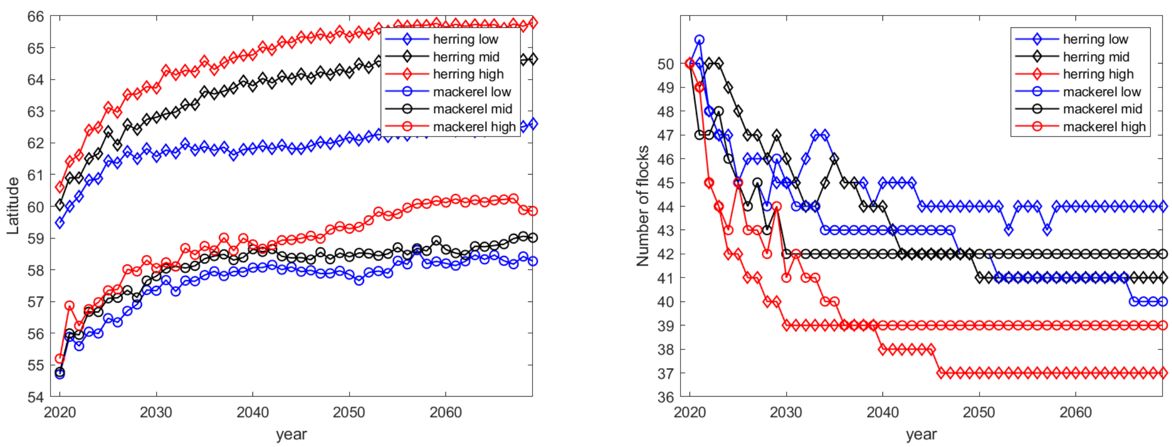
(c) Distribution of Herring in 2020: Low



(d) Distribution of Herring in 2070: Low

Figure 4: Herring Migration under Different Warming Up Trend

As 5 shows, the distance of the migration do depend on the seriousness of ocean warming. But no matter which case will prove true, two trends are for sure: the fish will migrate to the north and the population will decrease. However, there are difference between the two species. The herrings, living in colder waters from the beginning, still migrate faster than Mackerels. The reason is probably that a fairly large fraction of the mackerel population live in the Ireland water, where it's still relatively cool. Besides, the population decline is slightly larger for herrings. We have expected a larger variation in the declining speed because herrings are much less endurable to high temperature. But maybe the herrings are escaping very fast so that only a small fraction of the population is influenced.



(a) Center of Distribution

(b) Number of Flocks

Figure 5: The Evolution of the Distribution Center

As a summary for the results, if the ocean warms up quickly, the herring population will decline by 20% and they'll migrate 60°N to 66°N , while the mackerel population will decline by 25% and they'll migrate from 55°N to 60°N. If the warming up is mild, then the population loss of both species will be 10% and 20% respectively. Both of the species will migrate 3° toward north.

4 Fisheries Strategy: Challenge and Resolution

4.1 Economic Impact

[2] The vessels specialized in mackerel and herring landing are only a small fraction of the Scottish fleet. However, they are dominant in the industry in terms of income and cost. In 2016, the value of the Mackerel and herring landed sum up to 33.6 million pounds, more than 60% of the value of the whole fishery industry. Unlike other vessels for the demersal species and shellfish, pelagic fishing has a demand for large equipment. The companies running mackerel fishing usually have a large crew and vessels longer than 40 meters, which induces great cost every day. If the ocean warming process drives the fish flock north, the tremendous cost of long range fishing will offset its profit. The recent decline of recruitment and number of vessels will continue deteriorating.

Given the result simulated by the model, we now estimate the implied impact of ocean warming on Scottish pelagic fishing industry. According to Scottish Sea Fisheries Statistics 2016, 30 pelagic vessels are concentrated in three major fishing ground. Peterhead and Fraserburgh, close to each other, contribute to about two thirds of the total landing, while Shetland vessels, located in the northeastern corner of UK, harvest the rest. We simplify this fact by assuming all the vessels are on their average size, assigned to the two centers in proportion to their share of landing.

For a given year, we first estimate the operating cost given the distribution of the fish. For simplicity, we assume there is only one vessel for each fish with shares of the fleet equal to v_m and v_h respectively. There is instance during the season L that these ships can voyage. This distance is an analogy to the length of the fishing period. Each time we suppose the mackerel vessel knows where the location of the closest flock is and go for it, consuming a certain distance l out of its quota Lv_m. We assume the ship only fish one flock once a year. The next time, it go for the second closest flock for another landing, until it runs out of the distance quota. Since we have two headquarters. We assign each flock to one of them according to a share-weighted distance to each. Besides, we assume the harvest from each voyage is one unit and the total landing within one fishing period is given by:

$$I_{i,t} = \min_k \left\{ k | \sum_{j=1}^{k} l_{j.t} > v_i L \right\}, \quad i \in \{m, h\} \tag{20}$$

On account of the price fluctuation caused by the change in seafood supply, we assume that the demand elasticity of herring and mackerel is 0.5. Estimating the elasticity is beyond the scope of our report. A survey of literature shows that the variation of demand elasticity is large among all kinds of seafood. But the average of pelagic fish is about 0.5. Thus the equation for the revenue is

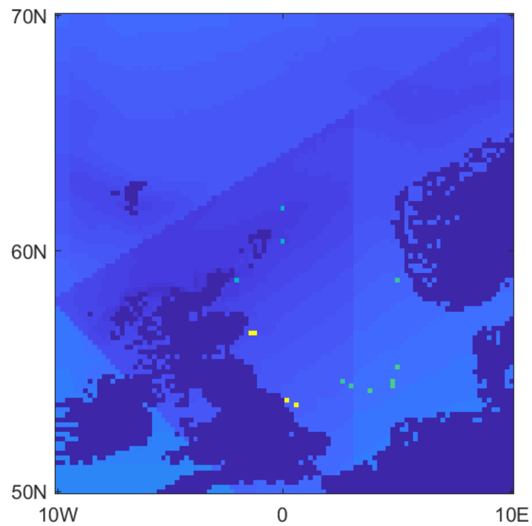
$$R_{i,t} = I_{i,t} P(I_{i,t}), \quad i \in \{m, h\} \tag{21}$$

Second, we adjust the cost in line with the structural change in the industry. The cost of pelagic fishing consists of the maintenance (and the insurance) cost, wage, depreciation and the fuel, among which the first one has the largest share. We assume the wage will keep still in the long run. Although the average number of days on board every year and the crew recruitment has both decreased since the early 2000s, the change is trivial compared to the impact of the fish's migration. We assume the cost on the fuel is proportional to the length of voyage. Since we also assume a constant fishing period represented by L [4] , this account will also be fairly stable. The most significant change in the total cost is, probably, induced by the rest two items. the maintenance and depreciation cost share the same assumption that given L, their cost imputed to the fishing period is proportional to the average length of each voyage, thus is approximately given by:

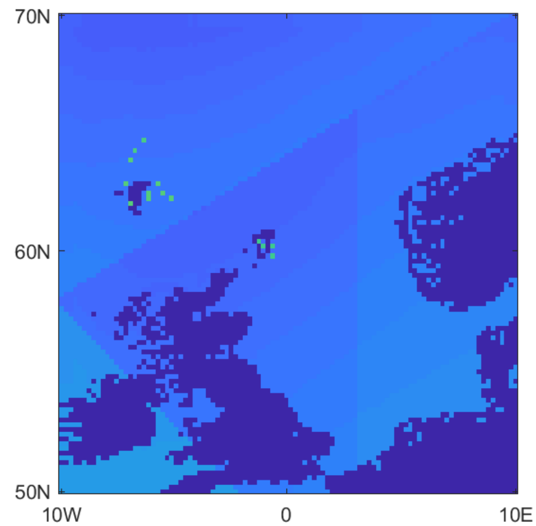
$$C_{i,t}^{dep} = C_{i,0}^{dep} (0.3 + 0.7 \frac{n_{i,t}^v}{n_{i,0}^v}), \quad i \in \{m, h\} \tag{22}$$

where n^v denotes the numbers of voyages made within one fishing season. We assume that 70% of the total cost is incurred during voyages and the rest 30% happens during fishing off season. This assumption implies that even if the number of days on the ocean is constant every year, the cost will still go up if the vessels are operating farther off shore. The intuition is that offshore fishing is more challenging and also riskier so that not only the vessel wears faster but also insurance, included in the maintenance category, is also more expensive.

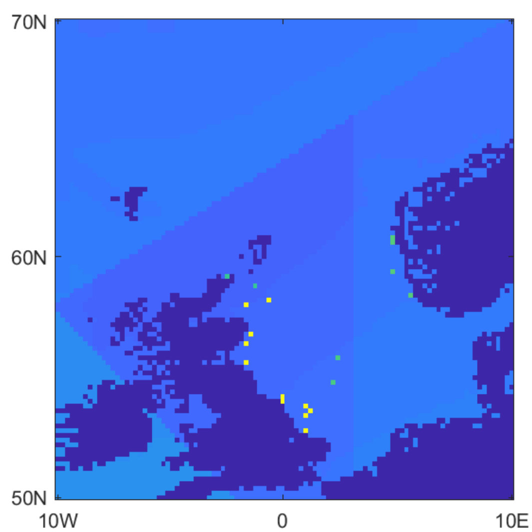
[4]But there will be "residual" distance left every year, analogous to one or two day left in the tail of the season that's too short for a voyage.



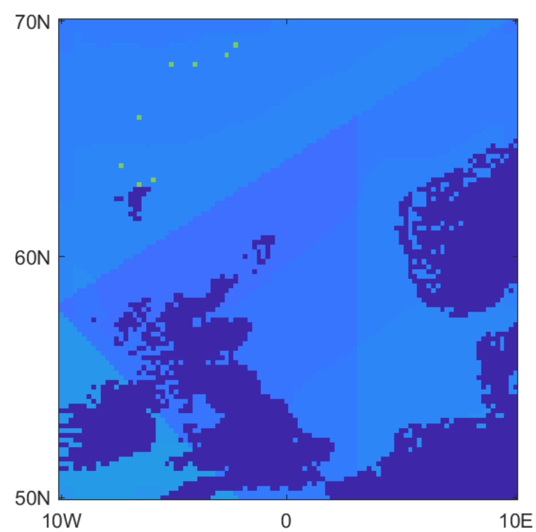
(a) Distribution of Mackerel landing: 2020



(b) Distribution of Mackerel landing: 2070



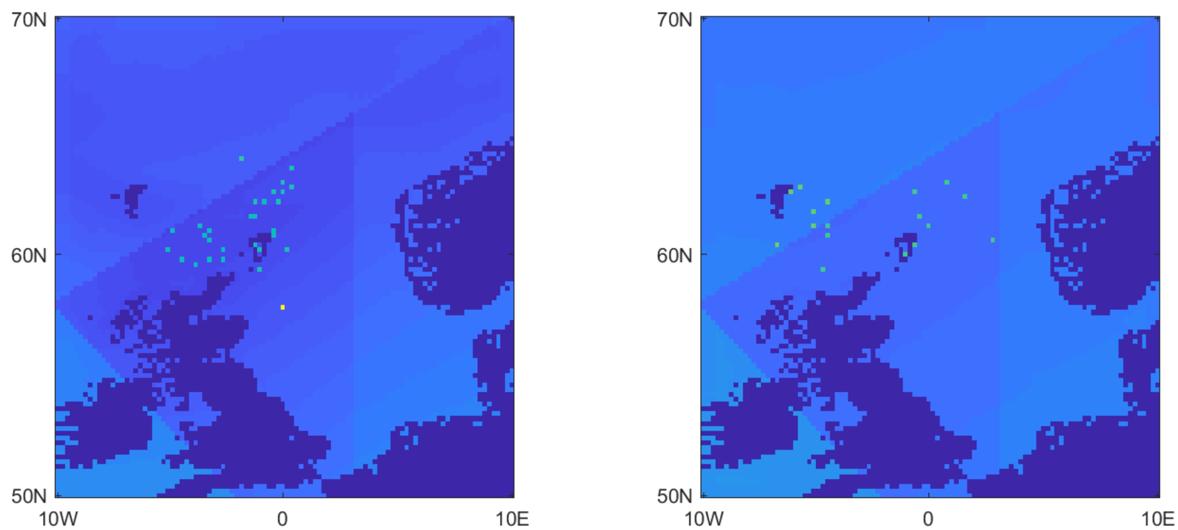
(c) Distribution of Herring landing: 2020



(d) Distribution of Herring landing: 2070

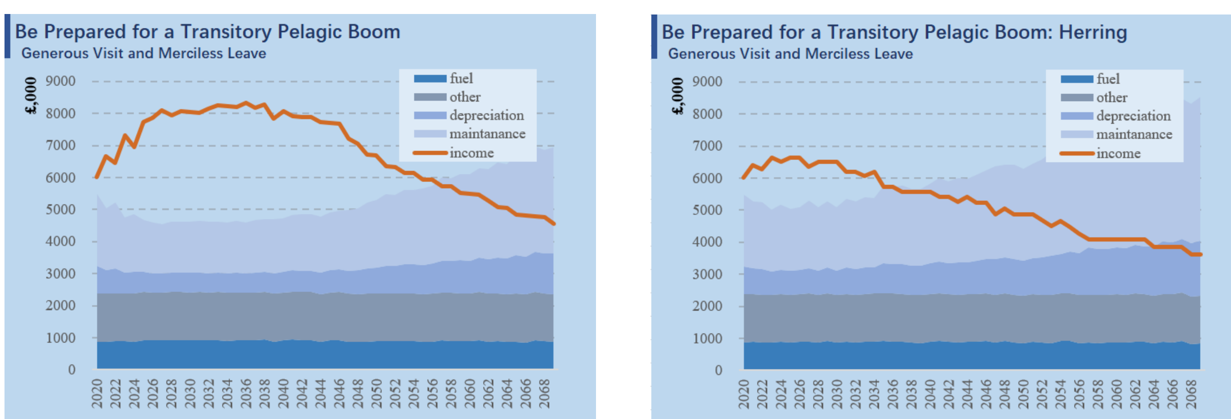
Figure 6: Mackerel and Herring migrate to the "Blue Ocean"

Now we're ready to relate our simulation with this cost-revenue analysis. The distribution of harvest in 2020, shown in 6c, is fairly realistic. Scottish vessels sail out to the southern and Norwegian North sea where flocks of mackerel emerge occasionally, which contribute to more than half of the annual harvest. However, mackerels disappear in the hot southern North sea due to a sharp ocean warming. In only 50 years, they will migrate to the Shetland Island and Føroyar island where the water is still suitable for living and breeding. Such irreversible shift will cause a great loss to the headquarter in Fraserburgh. The vessels harbouring there need to travel thousand of miles before they arrive at mackerels' new habitations. According to our calculation, their total cost will increase by more than 30%. However, the problem is less severe, or even somehow profitable in Peterhead. This industry center is not far from either Shetland (just at the gate) or Føroyar. And if we have a look at the harvest distribution in 2039, we will surprisingly find flocks of mackerels lingering nearby, saving the vessels there a lot of money and efforts. Our simulation shows that the tonnage of landing will increase. Even the price will respond to an excess supply, the revenue will still soar up to 8 million Euros. But the boom would only be transitional if the temperature keeps increasing. The heat will push the flock towards north and prevent the larva in the lower latitude from maturity. Finally, the stock will shrink and if the vessels in Fraserburgh don't merge to the north headquarter, profit will cease before 2060 due to high fuel and and maintenance cost[5].



(a) Distribution of Mackerel landing: 2039 (b) Distribution of herring landing: 2039

Figure 7: Midway to the "Blue Ocean"

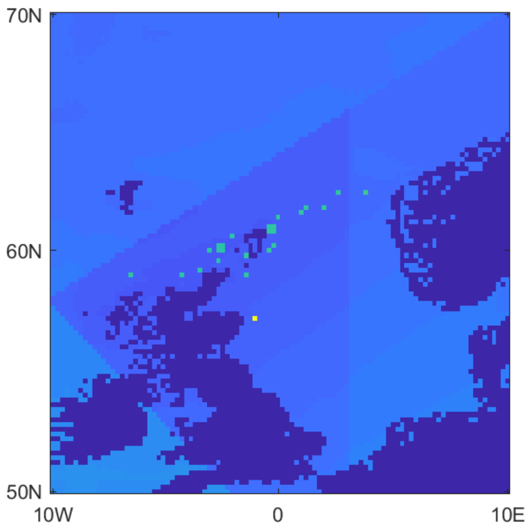


(a) Long run trend of profitability: Mackerel (b) Long run trend of profitability: Herring

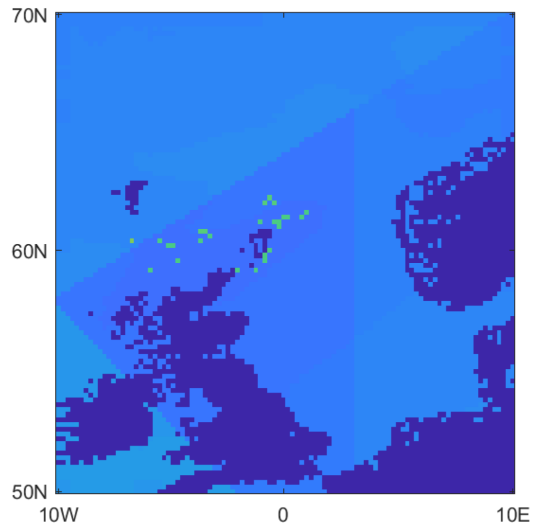
Figure 8: Long Run Trend of Profitability: Fast Warming

[5]Basic data source: https://www.gov.scot/publications/scottish-sea-fisheries-statistics-2018/

But what if the situation is not that bad? What if the temperature growth will cease at some point? Now we reflect our analysis given a slow warming up process estimated by our most conservative model. As shown by fig:dist.catch.low.2069, if the temperature rise only about 1°C in 50 years, then the fish in the Scottish Economic Zone is enough for the fishermen. Besides, the center of the flock is so close to the Shetland Island that vessels in Peterhead can make more money than they do now.

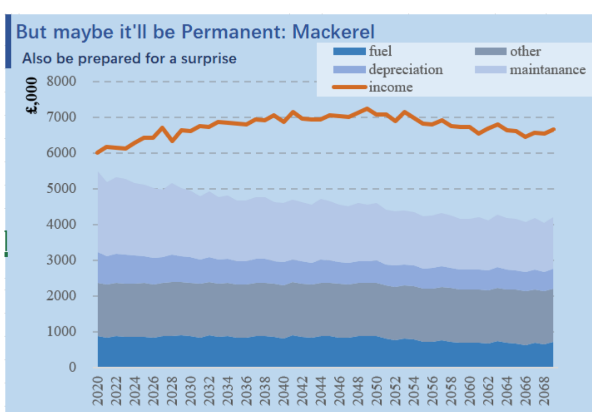


(a) Distribution of Mackerel landing: 2069

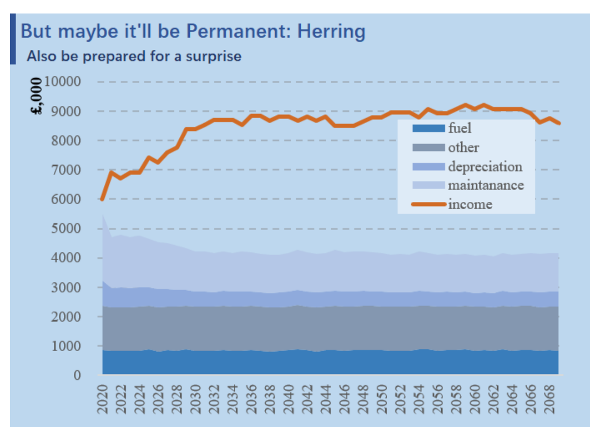


(b) Distribution of Herring landing: 2069

Figure 9: "Patriot" Fish: Beneficial Migration Under Slow Warming



(a) Long run trend of profitability: Mackerel



(b) Long run trend of profitability: Herring

Figure 10: Long Run Trend of Profitability: Slow Warming

4.1.1 Solution

Whether the ocean warming will be an opportunity or challenge to Scotland depend on the actual trend of ocean temperature. According to [4], the productivity of the Scottish water might even be mildly improved. Therefore, from our analysis, we can't exclude either situation. Thus we first state our advice suits both cases and then discuss situation-specific suggestions.

First, fish will migrate towards north in the following decades. Thus Peterhand will be preferable to the other headquarter in the south. We suggest that the industry can lean to the north and develop more fishing grounds around Shetland Island.

Second, in the face of a rising temperature, Mackerel would be generally more viable than herring because the former is more endurable under heat. For the same reason, herring will migrate faster than Mackerel. Thus we suggest to enlarge the share of Mackerel in the pelagic industry, not only because the population would be relatively larger, but also for that we can dispense the effort of offshore landing.

Third, we encourage small companies to cluster or merge into larger companies. According to [1], Norwegian fishery industry is scale economic both for coastal pelagic vessel or demersal-targeted trawler. We believe the Scottish fishery industry can also be benefited from scale economy once the Fraserburgh center merges to Peterhand. A larger company can do better in diffusing the fixed cost of an offshore fishing platform. It's also stronger in taking the risk of distant voyage and thus reduce the insurance cost. Besides, since the company will have some monopolistic power over the market price, it can come up with better plan for future production as well as avoid unsustainable landing.

If the temperature rise prove to be persistent, the above suggestion should receive more recognition. The industry could look for an alternative species as the major target for future landings since the structural change in temperature might be preferable to profitable creatures that didn't prevail previously. However, the population need time to grow. And given the dominant position of mackerel and herring in the current industry, the government should take action. They should look closely to the trend of landing tonnage. If there is sign of recession, they should plan in advance for an alternative industry. They should always have in mind an approximate time when the industry will cease to thrive, which is about 2060 in the worst case of our model.

If the warming up end up transitional, and the distribution of fish do shift north in a way favoring Shetland Island, then people can establish more fishing business centering Peterhand. The government could encourage pelagic fishing industry and related business such as dockyard and machine manufacturing. They can also encourage people to participate in the industry by subsidy, meanwhile encourage competition and regulate market price to ensure equity and efficiency within the industry.

4.2 Fish over the border

Scottish fishery was never a business of its own. During the past decades, British vessels have landed countless tons of aquatic product from EU Economic Area, especially from Norwegian waters. EU official contract prevent conflicts from occurring between fishing companies or fishermen from different member countries. However, public and governmental conversation over piscary and quota never ceased . As Britain withdraws from the EU, tremendous amount of effort has been made on negotiations over the right to fish in British water. So far, an agreement has reached that the current contract will hold for a while. But it's not guaranteed to be effective in the long run. And if the multilateral there will be more cases that a Scottish fishing vessel might want to cross the border for a profiting multitude of herring, which is not granted any more. Given that landings abroad used to contribute a significant amount to the total harvest. It's important to prevent the looming fights from happening and help the fishing industry grow in a healthy and peaceful way.

As our model suggests, if the temperature increase persistently, about 70% of the fish will be landed near Føroyar Islands. This island, well-known for its productivity, is however, also a land of international conflicts and disputation. Moreover, the residents there were never easy to deal with. For example, they tear up their contract with EU over the fishing quota and landing an annual amount of over 5 times of what's sustainable. Therefore Scotland, benefits most from the "Føroyar" fishing boom, should try to launch an international agenda. A new economic zone should be established. Quota should be fairly assigned. In order to facilitate the agreement, the government can reach economic contract with Denmark and invest fishing grounds in Føroyar. Scottish vessels can merge into an international company and employ Føroyar's local residents. These action will definitely, incur additional cost. If the negotiation cost exceed 10% of the total income, then the day when this industry cease to make profit would come 15 years earlier. Moreover, our model doesn't pay much attention to the Norwegian cost where Scottish fishermen land over 30 % of the fish. The government might also need to negotiate with Norwegian authority over the fishing quota if current contract under EU framework is abolished later. Therefore, the viability of pelagic fishing industry will be generally compromised. And our suggestion about plan for the industry's decline gains more weights.

However, if the climate change is mild, then most of the landings will happen within Scottish economic zone. Therefore, territorial affairs are not the first order concern. Again, our model underestimate the importance of Norwegian cost. But they are most likely still beyond Scottish territory. Therefore, the change in their status is less relevant to climate change.

5 Conclusions

We establish a physics-inspired model of fish migration dynamics, and find that if the ocean temperature continues to rise, herring and mackerel will migrate northward. At the same time, the temperature also affects the spawning rate of fish, causing a population decline.

Based on three different predictions of ocean warming (i.e. pessimistic, intermediate and optimistic), herring and mackerel will migrate northward with different speeds. As sailing distances of smaller-scale fishing enterprises is limited by objective conditions, the business will cease to make profit by 2054 in the worst case(2067 on average).

In the face of these difficulties, under the goal of minimizing the increase of fishing cost, it is necessary for these enterprises to move their fishing boats to the port in the north and adjust the proportion of fishing volume among all kinds of fish in time. Because mackerel is more adaptable to warm environment, enterprises should increase the proportion of mackerel catches and reduce herring's. At the same time, it is also worth considering to enhance the cooperation with fishery counterparts to disperse the fixed cost and increase influences on prices.

In addition, due to the northward migration of fish, a number of fish will enter the territorial waters of countries such as Norway and Ireland. In this regard, the Scottish government needs to strengthen its fishery cooperation with these countries.

6 Strengths and Weaknesses

6.1 Strengths

▲A physical-inspired model used to quantitatively describe the migration dynamics of the two fish species.

Instead of simply fitting, predicting and analyzing a large number of data, we give the migration dynamics of fish by analogy with the movement law of charged particles in the potential field in physics. Though it may be accurate to predict fish migration in the short term just by fitting the known data, the behavior would be powerless in a 50 year time span.

▲A detailed analysis of possible changes in costs and incomes, and a detailed fishery strategy based on it.

We reviewed the statistics of the cost and income of Scottish fishing vessels in detail, analyzed the influence of sailing mileage, fishing quantity as well as market prices on the profit of the fishery, where we have noticed the depreciation of fishing vessels and the relationship between the fish supply and its price.

6.2 Weaknesses

▲Not accurate enough

We divide the entire area into 100×100 cells, however, the side length of each cell is still more than 20 kilometers, which would harm the accuracy of the simulation.

▲some parameter values are subjective

For some parameter values, such as the charge q, we have only made rough estimates to bring them in line with the known data.

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[1] TROND BJØRNDAL and DANIEL V. GORDON. "The Economic Structure of Harvesting for Three Vessel Types in the Norwegian Spring-Spawning Herring Fishery". In: *Marine Resource Economics* 15.4 (2000), pp. 281–292. DOI: 10.1086/mre.15.4.42629327. URL: https://doi.org/10.1086/mre.15.4.42629327.

[2] Alena Lappo. "Analysis of cost of production in North Atlantic fisheries". In: (2013).

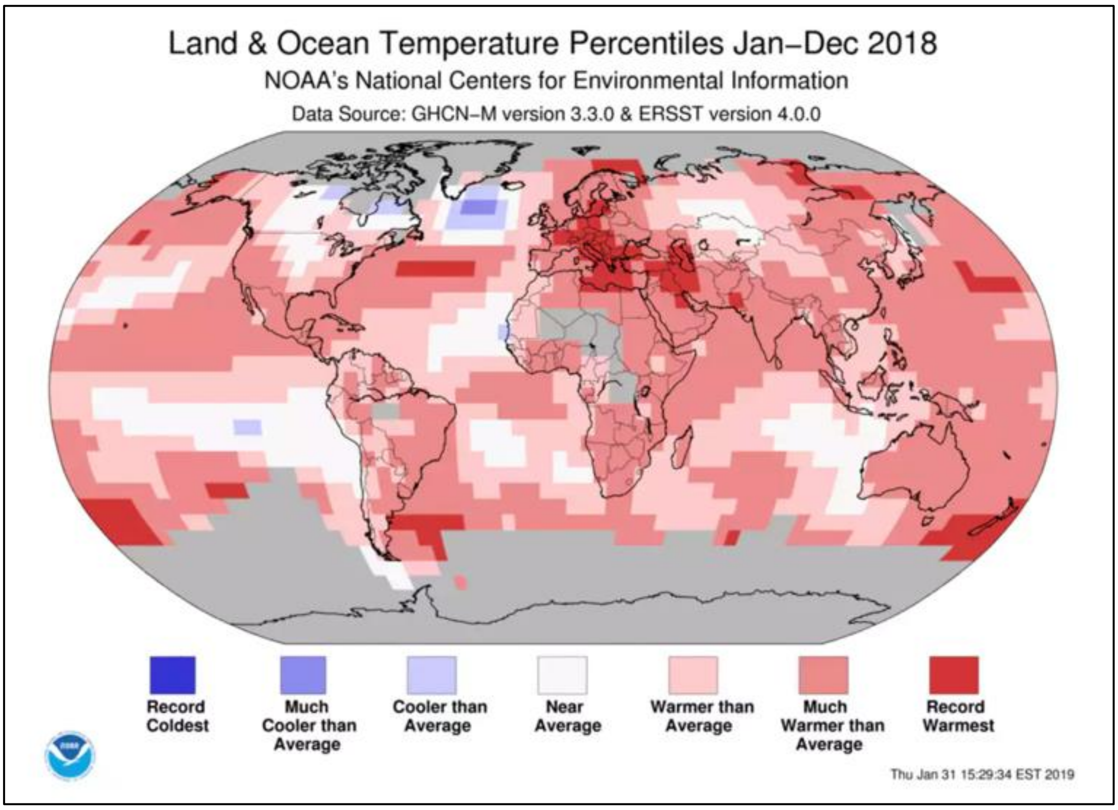
[3] Christopher Revell and Marius Somveille. "A physics-inspired mechanistic model of migratory movement patterns in birds". In: *Scientific reports* 7.1 (2017), pp. 1–10.

[4] Ussif Rashid Sumaila and William WL Cheung. "Cost of adapting fisheries to climate change". In: *World Bank Discussion Paper* 5 (2010), pp. 407863–1229101582229.

Oceans are warming! Fishes are moving!

Scottish fishery is facing challenges!

You must have heard of global warming, but do you think it is out of reach and has nothing to do with you? Then you are WRONG! Global warming has been causing seas around Scotland warmer, and fish living in this area, such as herring and mackerel, cannot survive in the warmer environment, so these fish will move to the north. As they move northward, your fishing vessel will have to sail more miles, and your fuel cost will increase significantly. What's worse, our calculations show that these fish may even migrate to the sea near the Faroe Islands and Norway in the next fifty years. Obviously, you cannot fish in the territorial waters of other countries (not to mention that Britain has just left the European Union). In addition, the warmer sea will also affect the birth rate of fish, and the total amount of fish will decrease accordingly. All of this can have a huge impact on Scottish fisheries.



Almost all oceans are warming, especially in Europe.

Even if the real situation in the future may not be as bad as we calculate, you should be prepared to deal with ocean warming. In fact, things will not change so fast, which means you have time to take actions to reduce the losses. Our team has made the following four suggestions, and we think they are worth considering for you:

First, try to move your fishing vessels to the northern fishing ports. Obviously, this will reduce your sailing mileage and your fuel costs. For example, we think Shetland Island is a good choice.

Second, adjust the proportion of different species of fish you catch. Just take herring and mackerel as an illustration. In the face of ocean warming, mackerel is generally more adaptable than herring, as the latter is more sensitive to warming seawater and therefore moves northward faster. Therefore, we think it is wise to expand the fishing proportion of mackerel. Not only is it easier to catch, but it can also reduce your fishing costs.

Third, strengthen business cooperation with your business partners. We believe that enterprise clusters would have significant advantages because they can better disperse fixed costs. It is also more able to bear the risks of long-distance voyages, thereby reducing insurance costs. In addition, your impact on fish prices will also increase, so you can plan better for future production.

Finally, since fish are likely to move outside Scottish waters, fishermen may ought to promote the government to carry out fisheries cooperation between Norway, Ireland and other countries. The British has just left the European Union, which is unfortunate news for the future development of Scottish fisheries. It would be necessary to express your voice to the government.

Scotland and its surrounding waters. Because of the ocean warming, fish is likely to migrate out of this area.

The above suggestions will help you pass the test of ocean warming and fish migration. Our calculation shows that it is possible to maintain the current annual profit basically when the first two suggestions are adopted. Apparently, the latter two suggestions are beneficial and harmless. ■