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GLOBAL WARMING AND FISH MIGRATIONS

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ABSTRACT. Ocean temperatures are expected to rise over the next decades. This is likely to affect the distribution of fish stocks between the exclusive economic zones (EEZs) of different countries. Such changes are likely to be triggered as temperatures rise beyond certain threshold levels, and they are likely to be irregular because temperatures are likely to vary around a rising trend. The paper looks at the case where temperature changes would displace a fish stock out of the EEZ of one country and into the EEZ of another, with a transition period in which the stock is shared. It is examined how this might affect the risk of extinction and degree of overfishing, under different cost scenarios and different assumptions about how countries react to observed changes in the distribution of the stock between their economic zones.

Introduction. It is widely believed that global warming is taking place. This does not just affect the atmosphere; the oceans are also expected to warm up. This warming, both in the atmosphere and the ocean, is expected to affect in particular Arctic and subarctic regions. Thus, within the next 100 years, a large part of the Arctic may become ice free during the summer months and open to shipping and perhaps even drilling for oil.

This warming seems likely to also affect fish stocks, and perhaps in particular those that inhabit Arctic and subarctic regions. These changes could be of two not mutually exclusive kinds. First, the productivity of fish stocks could be affected, positively or negatively and probably in different directions for different stocks. Secondly, the habitat for stocks could be displaced. Each species of fish thrives within its own specific temperature limits. A warming of the ocean could therefore spatially displace the habitat of fish stocks. In the Northeast Atlantic, the cod could move further northeast, away from the Norwegian coast and the Norwegian Sea and towards the Russian coast and into the Barents Sea (Stenevik and Sundby [2007]). Atlantic mackerel would be found further north, and so would Atlantic tuna. There are historical examples of such effects. A warming of the ocean off Iceland and Greenland in the 1920s and 1930s led to cod and herring migrating further north and to Greenlandic waters (Vilhjálmsson [1997], Stenevik and Sundby [2007]). In other parts of the world, changes in ocean temperature and currents are also likely to cause displacements of fish stocks. In some cases these temperature changes could affect the distribution of fish indirectly through changing the habitat and migrations of forage fish, rather than making the temperature intolerable for fish higher up in the food chain.

Because the exclusive economic zones (EEZs) are fixed upon the map, a displacement of fish stocks would affect the distribution of stocks between the EEZs of different countries. Stocks that now occupy the EEZs of a given number of countries might change their distribution in favor of some countries and to the disadvantage of others. Some stocks might even change from being located exclusively in one country's EEZ to becoming shared between two or more, or they might over time move completely into the EEZ of another country. Some stocks might also begin to spill over into the high seas, or vice versa.

For stocks that are shared between different countries, these changes could put the sharing agreements under strain. As a case in point, a so-called "regime change" in the climate of the North Pacific, not necessarily a part of a global warming, led to a breakdown in the agreement on salmon fishing between the United States and Canada.[1] If the distribution of a stock changes from being shared between two or more countries to being confined to the EEZ of only one, the latter country would have no incentive to honor an agreement based on the fish being accessible in other countries' EEZs. But before things have gone that far, it is quite possible that the agreement would break down and that the countries that appear to be losing the fish might take whatever they can while the fish is still available, causing perhaps an irreversible damage to the stock.

For stocks that start out as being confined within a single country's EEZ, the scenario might be even more precarious. If a stock starts to spill over into the zone of another country, or into the high seas, this will probably come as a surprise, and at first it would probably be considered a transient phenomenon. Furthermore, it is likely that the changes in fish distribution caused by changes in temperature will not be gradual and continuous but occur suddenly when certain temperature thresholds have been passed. Because temperatures are likely to fluctuate around a rising trend, these changes could occur with temporary reversals. For these reasons it is likely that agreements on stocks that over time become "shared" will take some time to be established. Time will be needed to assess the situation and to figure out the most adequate response, and in the meantime reality will have changed yet again.

In this paper we will look at the development over time of a stock that starts out as being confined to the EEZ of one particular country called Country One, but over time moves into the zone of another country, which we will call Country Two. Country One is assumed to initially manage the stock for its maximum profit, being the sole owner. As the ocean temperature increases, the stock starts to spill over into Country Two's zone. Country One, after discovering this, adjusts its exploitation with a time lag, entering into a noncooperative game with Country Two. While the temperature is assumed to be on a rising trend, there are assumed to be year to year random variations, affecting the distribution of the stock between the two countries and enticing both of them to revise their strategies. After a certain period of uncertainty in the stock distribution, the temperature will eventually have risen sufficiently to displace the stock permanently into the EEZ of Country Two, which will henceforth treat it as its own, after a certain time lag for realizing that a permanent change has indeed occurred. We shall concentrate on the displacement aspect, leaving aside the possibility that the productivity of the stock could also be affected. While a higher temperature would most likely increase the growth rate of fish in a given area, it is also possible that the fish will move into another area where the temperature is similar to where they used to be located, so that growth will not increase.

The questions we are concerned with are the following: How much overfishing might occur when a fish stock slips from sole ownership of one country to being exploited competitively by two countries? Is there risk of extinction as a result of this competition? How important is the time lag with which the countries adjust their expectations with regard to how much of the stock will be within their EEZ? We do not have any particular situation and fish stocks in mind, but offer a generic model that demonstrates what may happen as a result of stock displacement engineered by temperature change. Even if for practical reasons we rely on a numerical model, the results should be interpreted qualitatively and not quantitatively.

A question not considered in this paper is whether the countries would manage to cooperate on exploiting the stock during the phase when it is in transition between being the property of one country to becoming the property of another. Given that this phase is transient and perhaps not very long, it might not provide enough time to reach such an agreement, and any agreement would in any case become obsolete after a certain period of time. For stocks that would be displaced permanently from being under sole ownership to being shared the circumstances are different, but we leave that question to later research.

The model. Even if ocean temperatures may now be on a rising trend, they can be expected to fluctuate considerably around that trend. Figure 1 shows a time series of ocean temperatures in Norwegian waters since 1936. Over this time period no trend is discernable, but there have been considerable fluctuations. Such fluctuations are likely to continue even if temperatures follow a rising trend.[2]

To model the development in temperature over time, we shall use a random walk model with trend:

$$\Delta T = \mu + z \tag{1}$$

where T is temperature, μ is a trend parameter and z is a normally distributed random variable with an expected value of zero and a constant variance σ^2. Time is discrete and measured in years, and the temperature refers to an annual average.

The fish stock is assumed to grow according to the discrete logistic function

$$X_{t+1} = S_t + aS_t(1 - S_t) \equiv S_t + G(S_t) \tag{2}$$

where X_{t+1} is the stock at the beginning of year $t+1$, S_t is the stock left behind after fishing in year t and $G(\cdot)$ is the surplus growth function. The carrying capacity of the environment has been normalized at

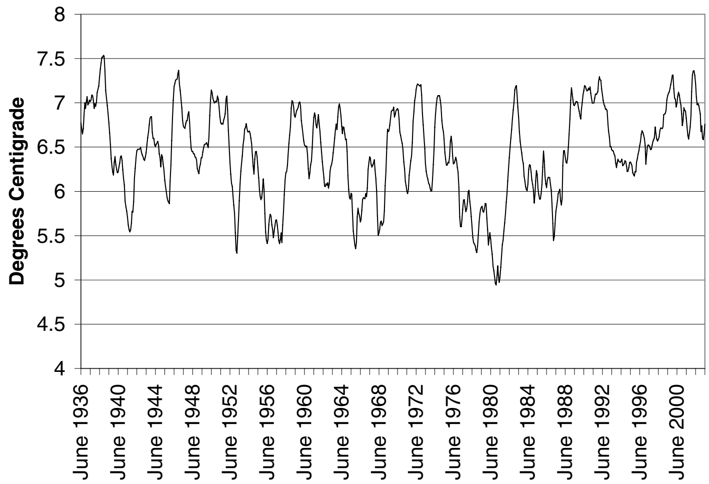

FIGURE 1. Twelve-months moving average of ocean temperatures in the uppermost 50 meters of the water column at Skrova in Lofoten. Source of primary data: Institute of Marine Research, Bergen.

one and is assumed not to be affected by the warming process, and neither is the maximum growth rate a. Warming thus only affects the geographical distribution of the stock.

Assuming that growth and decay of the stock take place after fishing, the total catch from the stock will simply be $X_t - S_t$. With a given price of fish and a unit cost that is constant and independent of the stock size, the net price (p) will be constant. A sole owner maximizing the present value of rents from fishing the stock will seek to maximize

$$p(X_0 - S) + pG(S)/r \tag{3}$$

where X_0 is the stock in the beginning of the first year (year zero), S is the optimal stock to leave behind after fishing in year zero and all future years and r is the rate of discount.

This is obviously a special case but with important implications for the likelihood of irreversible destruction of the fish stock, as is well known from the literature.[3] Due to technological and environmental circumstances, the catch per unit of effort does not fall as the stock is depleted, and the last fish can be scooped up profitably if any fishing at all is profitable. These circumstances appear to characterize fish that travel in shoals and are caught with technologies that seek and encircle these shoals, such as the purse seine.[4]

To deal with the case of stock-dependent unit costs we shall use the time-honored Schaefer function, which also is a special case, but at the opposite extreme. In the Schaefer function, the catch flow (y) is proportional to the stock (s) and the fishing effort (E) applied. With a constant cost (c) per unit of effort, the unit cost of the catch is $cE/qEs = c/qs$, so that the rent in each period is[5]

$$\int_S^X (p - c/s)\,ds = p(X - S) - c(\ln X - \ln S). \tag{4}$$

The sole owner would in this case maximize

$$p(X_0 - S) - c(\ln X_0 - \ln S) + [pG(S) - c(\ln(G(S) + S) - \ln S)]/r. \tag{5}$$

The distribution of the stock is assumed to be governed by ocean temperature so that the entire stock is within the EEZ of Country One when the temperature is below a certain threshold level T_1 and within the EEZ of Country Two if the temperature exceeds another and a higher level T_2. Within these limits the stock is assumed to be split between the zones of the two countries in proportion to the difference between the actual temperature and these limits.[6] Formally,

$$\begin{aligned} b &= \mathbf{1} \quad \text{if} \quad T < T_1 \\ b &= \frac{T_2 - T}{T_2 - T_1} \\ b &= \mathbf{0} \quad \text{if} \quad T > T_2, \end{aligned} \tag{6}$$

where b denotes the share of the stock that is within the EEZ of Country One.

The model starts off with an initial $T_0 = 0$, with T developing according to (1) after that. This means that the stock is initially in the EEZ of Country One, but as the temperature drifts upward over time, Country One suddenly finds that some of the stock has spilled over into Country Two's EEZ. Because of the stochastic element in (1), the share of the stock in Country One's zone will vary henceforth, and the stock may even return in its entirety to Country One's EEZ for some time, but ultimately the entire stock will end up in the EEZ of Country Two. Figure 2 shows samples of the temperatures and the implied stock distributions over a time horizon of 100 years. Due to the random element in the temperature change the possible paths can be quite different, even if all show a rising trend.[7]

It is reasonable to assume that Country One will act upon the new distribution of the stock with some reluctance and time lag. First, it will take time to discover what actually has taken place. Even if the ocean temperature can be monitored on an ongoing basis, there will be no factual experience and perhaps limited research to support any notion of how the distribution of the stock may be affected by a change in temperature. We assume that the authorities will react to the change in the distribution of the stock with a time lag of one year. Then, even if the distribution of the stock last year is fully known, it is not likely that the authorities will regard this as a permanent and new distribution pattern. The first time it happens it is likely to be seen as an aberration, meriting limited response but indicating a risk that previously had not existed. We shall assume that the authorities in Country One react to the change in the distribution of the stock by updating their expected distribution (β) of the stock as follows:

$$\beta_t = (1-\gamma)\beta_{t-1} + \gamma b_{t-1}, \tag{7}$$

i.e., the expected distribution of the stock is updated each year according to the experience from last year, with the parameter γ being the weight that is put on the latest available evidence. The value of this parameter could be important, and we will experiment with different values. Furthermore, γ could be time-dependent, in that experience of repeated changes in b would probably be given more weight than the first time b happens to change. We will not pursue this further here. Furthermore, we assume a symmetric reaction from Country Two. A possible extension would be to explore the consequences of asymmetric reactions.

In the period when the stock is split between the zones of the two countries, the sole ownership assumption no longer holds. During this period the two countries are assumed to select a strategy that maximizes the expected present value of their rents, given the strategy of the other party. As argued above, no coordination is assumed to take place between the players in this period. The expected future

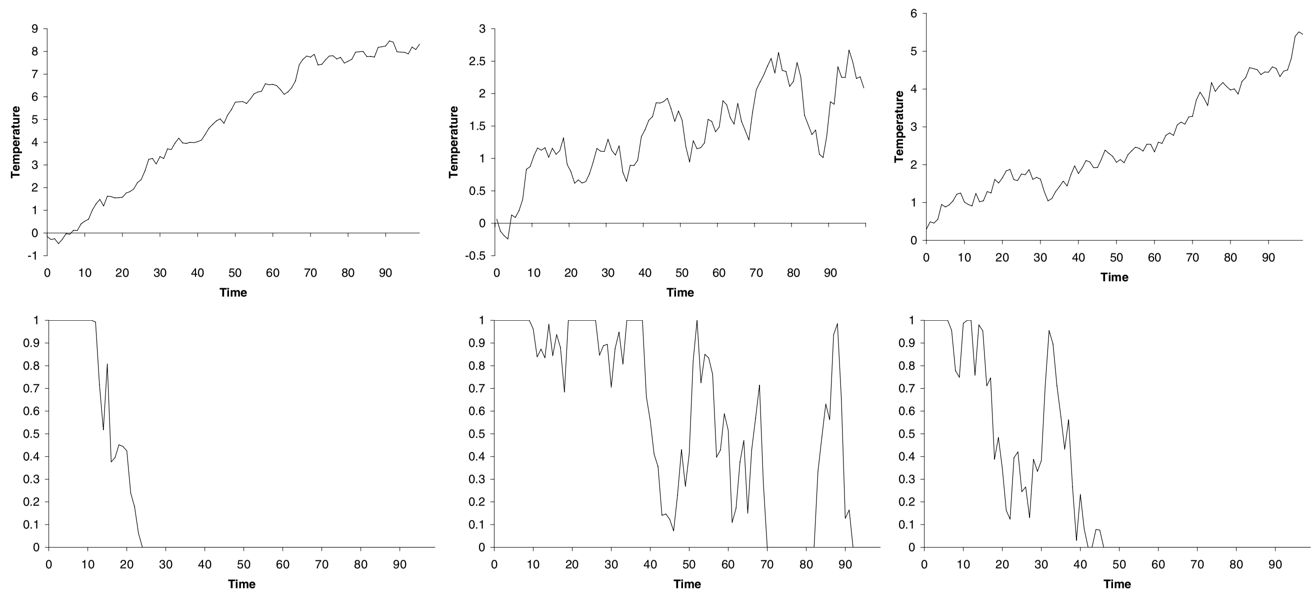

FIGURE 2. Three examples of development of temperature over 100 years (upper panel) and the implied share of the stock in the EEZ of Country One (lower panel).

distribution of the stock is assumed to be given by equation (7). This raises two questions: (i) what are the strategic variables of the two players, and (ii) what characterizes, in greater detail, the distribution of the stock and migrations between the two zones?

There are three candidates for strategic variables: the catch volume, the fishing effort applied and the stock left behind after fishing. Catch might be a strategic variable of choice if the price depends on the catch volume, which we have assumed not to be the case. We will use the stock left after fishing as a strategic variable, which implies that there is enough fleet capacity always to take the difference between the initial stock and the stock desired to be left over after fishing. Constraints on available fishing capacity would invoke fishing effort as a strategic variable.

As to stock distribution and migration, we shall make the following simplifying assumptions. The distribution of the stock at the beginning of the fishing period is given by the temperature that year (equation (6)). After that, the stock stays within each country's EEZ until the fishing is over. Then the stock left in both zones grows and breeds as a unit, and the stock emerging at the beginning of the next year distributes itself according to equation (6).

In the period when the countries share the stock the rent maximization problem in the constant unit cost case becomes

$$p[\beta X_0 - S_1] + p[\beta G(S_1 + S_2) + \beta(S_1 + S_2) - S_1]/r \tag{3'}$$

and analogous for Country Two, with β being replaced by $1 - \beta$. The variables S_1 and S_2 refer to the stock levels left after fishing in the two countries' respective zones.

For the stock-dependent unit cost case we get

$$\begin{aligned} &p(\beta X_0 - S_1) - \beta c[\ln \beta X_0 - \ln S_1] \\ &\qquad + \{p[\beta G(S_1 + S_2) + \beta(S_1 + S_2) - S_1] \\ &\qquad\qquad - \beta c[\ln \beta(G(S_1 + S_2) + (S_1 + S_2)) - \ln S_1]\}/r. \end{aligned} \tag{5'}$$

Note that the cost parameter c is multiplied by the distribution factor β (for Country Two it would be $1 - \beta$). The reason is that with the same cost per unit of effort the break-even stock level (the level at which further fishing becomes unprofitable) is the same for both countries in terms of stock density, provided the stock is uniformly distributed over an area of a given size, which however may be displaced in space from year to year.[8] This density corresponds to different stock levels in absolute numbers in the two countries' zones. With an overall break-even stock level of c, βc will be in Country One's zone and $(1-\beta)c$ in Country Two's zone. Different break-even cost levels for the two countries would obviously affect the solution to the maximization problem, but for reasons of simplicity we have chosen not to pursue that question here.

In the following two sections we shall look into possible development scenarios for the stock and the fisheries, for the two cost cases discussed above. These scenarios were created by running 1,000 simulations of the fishery, each covering a period of 100 years. The parameters in equation (1) were set to $\mu = 0.05$ and $\sigma = 0.2$. Note that no particular measurement scale for temperature is implied. The two critical limits (equation (6)) were set at $T_1 = 1$ and $T_2 = 2$.

Constant unit cost and the risk of extinction. Maximization of the present value of rents (expression (3′)) implies

$$\beta G'(S_1^0 + \overline{S}_2) + \beta - 1 - r = 0 \tag{8a}$$

$$(1-\beta)G'(\overline{S}_1 + S_2^0) - \beta - r = 0. \tag{8b}$$

The bar over a variable denotes that it is taken as given and set by the other country. For the case of sole ownership, we have (8a) with $\beta = 1$ and $S_2 = 0$ (or (8b) with $\beta = 0$ and $S_1 = 0$).

One thing is immediately obvious; (8a) and (8b) cannot hold simultaneously except for the special case of $\beta = 1/2$. What this means is that the country with the smaller share has no incentive to leave behind any of the stock in its own zone.[9] More than a half of the benefit of any stock left behind by the minor player would go to the major player. Furthermore, in this particular setting, the minor player can ride for free on the conservation efforts of the major player, as some of the benefits of the stock left behind by the major player will spill over into the zone of the minor player.

In fact, the situation could be more precarious than this. For the major player, we need $G'(S) = (1+r-\beta)/\beta$ (or $G'(S) = (r+\beta)/(1-\beta)$ if $\beta < 1/2$) for $S > 0$. From (2) we have that $\max G'(\cdot) = G'(0) = a$. Hence, if the maximum (marginal) growth rate is too low, the stock would become extinct as a result of profit-maximizing even under sole ownership.[10] With a shared stock this result becomes more likely. Figure 3 shows the critical values of β for different values of a and a given r. Under sole ownership this extinction result translates into saying that the stock must yield a rate of return that is at least as high as the required rate of return on assets in general. For shared stocks the return accruing to the dominant player from leaving behind one unit of the stock must be equal to the required return on alternative assets.[11] From Figure 3 we see that if a is less than some critical level, which depends on the rate of discount, one of the players must be sufficiently dominant if extinction is to be avoided. If both players are too similar in size (how similar is seen to depend on a and r), neither of them will have a strong enough incentive to preserve the stock, as their individual returns on saving one unit of fish will be lower than the return on the alternative asset. The question of extinction as a result of a changed distribution of the stock will be seen to depend on the likelihood that the assumed shares enter the "danger zone" shown in Figure 3. In the simulations we are about to report, we have used $a = 1$, which means that extinction will occur if the two countries' shares of the stock are close to equal, as can be seen from Figure 3.

Now to the results of the simulations. The curves in Figure 4 show the probability that the stock will have been fished to extinction before a certain year, for different values of the expectation adjustment parameter γ. We see that for a very slow adjustment in expectations ($\gamma = 0.1$), there is a high probability that the assumed stock shares will become approximately equal and that the stock will go extinct before the 100 years are over; the probability of this is just above 0.95. With a more rapid adjustment of expectations it is more likely that the assumed shares will skip the danger zone; with $\gamma = 0.25$ the probability of the stock going extinct within the 100 years horizon drops to about 0.75. And with still more rapid adjustment it becomes lower still; for $\gamma = 0.5$ or greater the probability of extinction within 100 years drops to almost one-half.

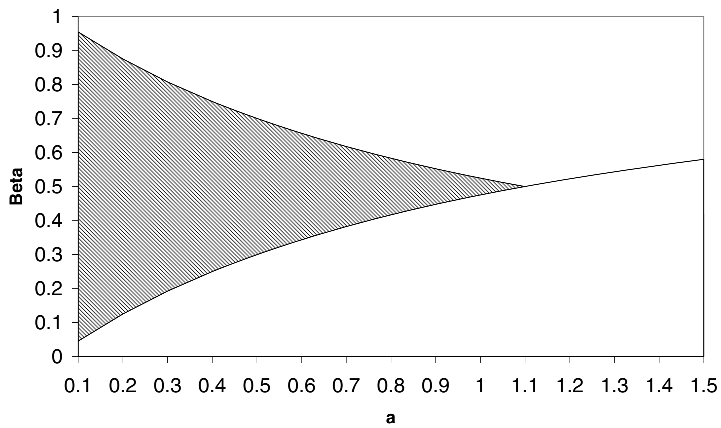

FIGURE 3. Critical values of β as a function of a, for $r = 0.05$. The shaded area shows values implying extinction.

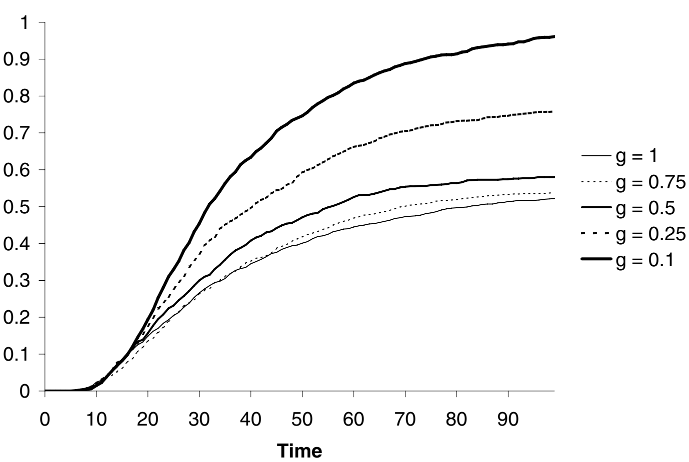

FIGURE 4. Probability that the stock will become extinct before a given year over a 100 years time horizon. Numbers in legend refer to the value of the expectations parameter γ.

This result is as disconcerting as the reasons for it are obvious. What is at stake is "skipping" the danger gap (the shaded zone in Figure 3) where the share parameters for the stock are close to equal. Over time the stock will go from being fully confined to the zone of one country to becoming enclosed in the other, b will fall from one to zero and so will the assumed share β. But if both countries are slow enough in revising their β and $1-\beta$, they are bound to enter the danger zone and the stock will be fished to extinction. If they revise their expectations more in line with the actual value of b, we might draw some luck from b actually skipping over the danger zone and dragging β with it. The more b changes, the more likely it is that the danger zone will be avoided. Given that b will in any case fall from one to zero, a more gradual change would be more likely to get into the danger zone. We thus reach the perhaps unexpected conclusion that more rapid environmental changes would in fact reduce the risk of stock extinction.

Figure 5 shows one case where the stock does go extinct. In year 15 the parameter β enters the danger zone and stays there long enough that in year 25 the stock becomes extinct.

Unit cost depends on stock: The Schaefer case. When the unit cost of fish depends on the stock, as with the Schaefer function, extinction is ruled out. But competitive exploitation of a shared stock could push the stock close to the break-even level and lead to diminished fish catches.

From (5′) we get the first order condition for maximum present value of rents:

(9a)

$$p[\beta G'(S_1^0+\overline{S}_2)+\beta-1-r]+\frac{\beta c(r+1)}{S_1^0}-\frac{\beta c[G'(S_1^0+\overline{S}_2)+1]}{G(S_1^0+\overline{S}_2)+S_1^0+\overline{S}_2}=0$$

(9b)

$$p[(1-\beta)G'(S_1^0+\overline{S}_2)-\beta-r]+\frac{(1-\beta)c(r+1)}{S_1^0}-\frac{(1-\beta)c[G'(S_1^0+\overline{S}_2)+1]}{G(S_1^0+\overline{S}_2)+S_1^0+\overline{S}_2}=0$$

Again, the condition for the sole owner case is given by setting $\beta(1-\beta)$ equal to one and S_2 (S_1) equal to zero.

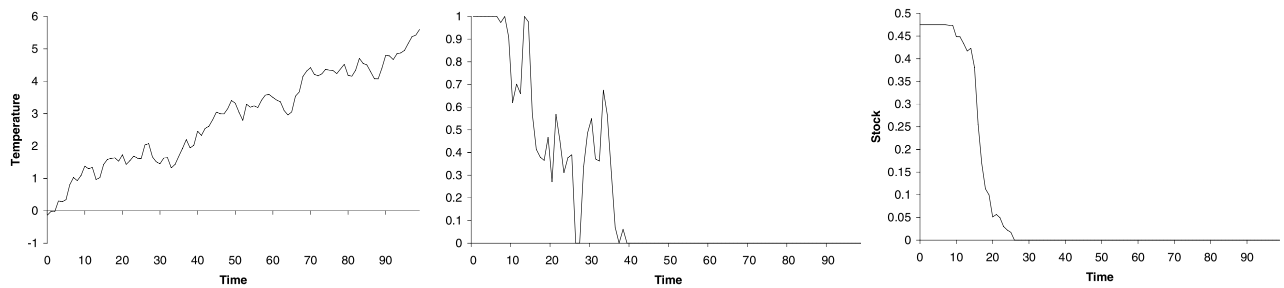

FIGURE 5. A case where the stock is fished to extinction within 100 years. From left to right: Temperature, implied share of the stock in Country One's EEZ and the stock left after fishing.

The mutually consistent solutions of these equations give us the stock left after fishing, with two caveats. First, there might not be enough fish in Country i's zone to leave behind the level it desires. Recall that the expected share of the stock assumed to return to Country i's zone is not necessarily the same as the actual share in any given year and, furthermore, the expected share is revised on the basis of last year's experience. If unexpectedly few fish turn up in Country i's zone, it might not be able to leave behind as many as it would wish. In that case, Country i is assumed to refrain from fishing.

Secondly, fishing the stock down to the desired level might be unprofitable, in the current year, for Country i. Suppose Country i expects few fish to turn up in its zone. It would therefore desire to leave behind few fish (more than βc, but this is a small number if β is small). If, however, unexpectedly many fish turn up in Country i's zone, it would not be profitable to fish the stock down to the desired low level. A larger stock would be spread over a larger area, and the planned number of fish to be left behind would correspond to a much lower and possibly unprofitable density of the unexpectedly large stock. The fishermen would observe a falling catch per unit of effort and falling profits as they deplete the stock. We assume that they stop fishing when the stock has been depleted to the break-even level (bc or $(1-b)c$, respectively).

Using (9) with these caveats allows us to find the stock left behind in each year. Figure 6 shows the average stock left after fishing each year, as well as the maximum and minimum stock, for different values of the expectation parameter γ. The curve showing the average stock bends downwards in the first half of the 100 year time period. This is when the temperature is likely to enter the interval in which the stock is gradually shifted from the EEZ of Country One to the EEZ of Country Two. The stock goes from being under sole ownership with an optimal escapement level of 0.553 to being competitively exploited by the two countries. It is well known that such competitive exploitation results in a smaller stock being left after fishing. We note that the more slowly the expected shares of the stock are revised, the smaller is the stock left behind on the average. The explanation for this is straightforward and similar to the one that was invoked above in the case of extinction. If the stock shares are revised only slowly, the transition from sole ownership by Country One to sole ownership by Country Two takes longer and causes a more prolonged over-exploitation compared with a quick updating of the share parameter. The same story is told by the minimum stock level attained in any given year. With a slow revision of these expectations ($\gamma = 0.1$) there is always some temperature scenario in which the stock will be driven down to the break even level in every single year, apart from the very first years. The maximum stock attained in any year is not very sensitive to how the expectations are revised, but it tends to vary more, and from earlier on, the quicker the revision of expectations.

It may be noted from Figure 6 that the maximum stock left behind after fishing is slightly larger than what the sole owner would find optimal. The reason for this is the following. The sole owner notices with a time lag that he has lost his total control of the stock, and he revises his expected share gradually. He therefore leaves behind more fish in his zone than his actual share warrants. At the same time, some of the fish that slip into the other country's zone will be left behind. In sum, this may amount to more than the sole owner would have left behind if he had had full control.

Figure 7 shows what happens with the catch. On the average the catch is relatively stable, but different temperature scenarios give rise to widely different catch profiles. There are cases where the catches fall to zero and others where they are twice as large as the average. A quick revision of expected stock shares produces the most stable average catch but also the largest differences between the maximum and the minimum catch in any year. For an immediate revision of expectations in line with last year's experience there is almost always some temperature scenario where no fish is caught in any given year, apart from the very first years. With the conservative revision of expectations the catch never falls to zero. This last effect is a mirror-image of the result that these expectations always produced some cases of the stock falling to the break-even level. But it need not be a bad thing that the stock occasionally falls to the break-even level; some fish is being caught, and no fish produces no revenues and no profits. The catch also varies less between different temperature scenarios when the expected shares of the stock are revised slowly, especially towards the end of the time horizon.

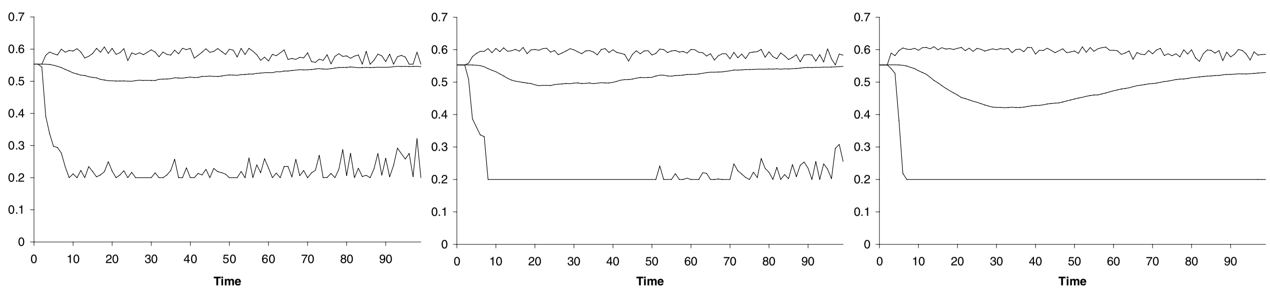

FIGURE 6. The average, maximum and minimum stock left behind in any given year, for $\gamma = 1$ (left), $\gamma = 0.5$ (middle), and $\gamma = 0.1$ (right).

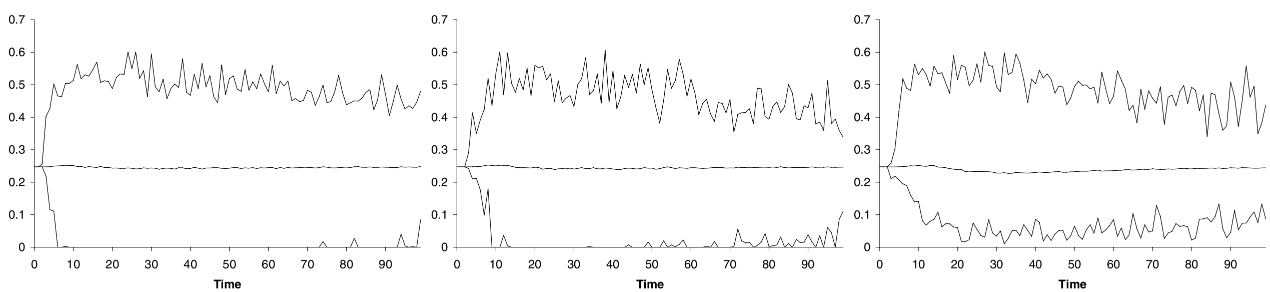

FIGURE 7. The average, maximum and minimum catch of fish in any given year, for $\gamma = 1$ (left), $\gamma = 0.5$ (middle) and $\gamma = 0.1$ (right).

Conclusion. Changes in ocean temperature, or the ocean environment in general, are likely to affect the geographical distribution of fish stocks. This would change the way in which stocks are distributed between the EEZs of different countries and could in some cases move stocks permanently out of one country's zone into that of another, over some time of transition. This would put fish stocks previously controlled by a single country under stress. We found that stocks with a constant unit cost of fishing would be exposed to a risk of extinction in a transition phase where no single party perceives having a sufficiently large share of the stock. A slow rate of expectations adjustment would in fact increase this risk; the more slowly the countries' expected shares of the stock change over time, the less likely it is that the stock will skip the danger zone where the two countries' shares are not sufficiently unequal.

Stocks characterized by stock-dependent unit costs are protected from extinction by a positive break-even level below which fishing becomes unprofitable. The transition from sole ownership to sharing the stocks, and then to a sole ownership again but a different one, will lead to some and temporary stock depletion, and the fish catches may fall to nothing in some years. While a conservative revision of expected stock shares would lead to the most severe stock depletion, it is also the one that best would avoid very low or zero fish catches.

ENDNOTES

1. See Miller and Munro (2004).

2. These temperatures are from Skrova in Lofoten and are one of the longest series available for Norwegian waters. This series is highly correlated with other measurements from northern Norway, but less so for measurements taken in middle and southern Norway. The longest time series from the northern waters is the Russian Kola series, beginning in 1900. This series shows rising temperatures from the early 1900s to the 1930s, but after that the development has been similar to the one shown in Figure 1 (cf. Stenevik and Sundby [2003]).

3. See Clark [1973, 1976] and Hannesson [1993].

4. See Bjørndal [1987].

5. We normalize and set $q = 1$ henceforth.

6. The temperature is assumed to be measured at a certain location in Country One's zone. With a given temperature differential vis-à-vis that location, the fish would be seeking their preferred and cooler temperature in Country Two's zone as the temperature in Country One's zone rises.

7. How different depends, needless to say, on the variance of the random element. In these calculations we have used $\sigma = 0.2$.

8. Obviously the stock density could be affected by its spatial displacement. Taking this into account would considerably complicate the model at hand without apparently adding much in qualitative terms.

9. It is assumed that the surplus growth function is concave, so that $G''(S) < 0$. Suppose that $\beta > 1/2$ and that (8b) holds with strict equality. Then, (8a) will be positive, and Country One (the major player) would want to leave behind more fish. Country One would want to do this until (8a) holds with equality. Then, (8b) would be negative, and Country Two (the minor player) would want to leave behind less fish, but it cannot leave behind less than nothing, so this inequality of (8b) is compatible with maximization of rents.

10. This result was first derived by Colin Clark (see, for example, Clark [1973]).

11. Leaving behind a marginal unit gives the major player a return of $\beta(1+G'(\cdot))$, while the alternative asset yields $1 + r$. Setting these two equal gives equation (8).

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