Economic impacts on key Barents Sea fisheries arising from changes in the strength of the Atlantic thermohaline circulation

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Abstract

A bioeconomic model of key fisheries of the Barents Sea is run with scenarios generated by an earth system model of intermediate complexity to assess how the Barents Sea fisheries of cod (*Gadus morhua*) and capelin (*Mallotus villosus*) are affected by changes in the Atlantic thermohaline circulation (THC) arising from anthropogenic climate change. Changes in hydrographic conditions have an impact on recruitment success and survival rates which constitute a lasting effect on the stocks. The economic development of the fisheries is assessed for the 21st century, considering a purely stock size based and a coupled stock size-hydrography based harvesting strategy. Results show that a substantial weakening of the THC leads to impaired cod stock development, causing the associated fishery to become unprofitable in the long run. Simultaneous improvements in capelin stock development help the capelin fishery, but are insufficient to offset the losses incurred by the cod fishery. A comparison of harvest strategies reveals that in times of high variability in stock development, coupled stock size-hydrography based management leads to more stable economic results of these fisheries than the stock size based fishing strategy.

Key words

bioeconomic modeling, Barents Sea, cod, capelin, thermohaline circulation

1. Introduction

The thermohaline circulation in the Atlantic Ocean is of great importance to Northern Europe because of the vast amounts of heat transported northwards, causing average temperatures in Northern Europe to be up to 10°C higher than the global zonal average of these latitudes (Rahmstorf & Ganopolski, 1999). Changes in the strength of the THC will have a pronounced impact on Northern Europe: simulations with coupled ocean-atmosphere general circulation models suggest that average temperatures over the North Atlantic drop considerably if the THC were to weaken or shut down completely (Vellinga & Wood, 2002; Kuhlbrodt *et al.*, 2007; Vellinga & Wood, 2007). Considering the expected underlying global warming trend, the net effect would be slight cooling of Europe with a stronger temperature effect occurring only along some coasts in northern Europe.

The Scandinavian coasts and the Norwegian and Barents Seas are expected to be particularly affected by changes in THC strength. Global warming is expected to have a profound influence on biological production in the Barents Sea, with primary production increasing and the species composition of plankton shifting from Arctic species to Atlantic species (Ellingsen *et al.*, 2008). This generally positive effect could be offset, as a weaker THC results in a reduced availability of plankton, which is an important food source for many fish species. Furthermore, survival chances of cod larvae would decline because of less favorable drift trajectories owing to altered circulation patterns, thus creating an additional obstacle for successful stock recruitment (Vikebø *et al.*, 2005; Vikebø *et al.*, 2007).

On the other hand, water temperatures in the spawning ground of Northeast Arctic cod (or: Arcto-Norwegian cod; *Gadus morhua*) and capelin (*Mallotus villosus*) are likely to increase as a consequence of anthropogenically induced global warming. Studies of stock development as a function of environmental conditions indicate that recruitment success of cod increases with warmer average water temperatures (Nilssen *et al.*, 1994; Ottersen *et al.*, 1994; Stenevik and Sundby, 2003). Depending on which effect has the greater influence on recruitment success, the change in hydrographic conditions brought about by a weakened THC is either beneficial or detrimental to the overall development of the Northeast Arctic cod stock. Additional complexity arises from the effects of interactions between the species of the marine food web of the Barents Sea. Hjermann and others (2007) quantify the nature and extent of these interactions for the three main fish species of the Barents Sea, indicating how predation of herring on capelin creates feedbacks concerning the cod stock development.

The effects of changes in hydrographic conditions on the capelin stock are somewhat unclear. Simulation results indicate that the range of capelin would extend further to the North in a warmer Barents Sea (Roderfeld *et al.*, 2008), with additional spawning areas being utilized close to the island of Novaya Zemlya (Huse and Ellingsen, 2008). However, this proposed shift has yet to be confirmed by observational data. Moreover, warmer temperatures increase the predation pressure from species feeding on capelin and their larvae, since warming would lead to an increased likelihood of young herring preying extensively on capelin larvae in the Barents Sea, thus significantly reducing recruitment success of individual year classes (Gjøsæter and Bogstad, 1998).

On the other hand, the development of capelin as a planktivorous species depends substantially on the abundance of zooplankton in the Barents Sea. In general, there is an inverse relationship between zooplankton and capelin abundance, with large zooplankton abundances in years of small capelin stock sizes (Gjøsæter *et al.*, 2002), which in turn has consequences for cod as well. Juvenile cod have to switch to macrozooplankton if not enough capelin is available as food source. However, a larger share of amphipods and krill in the cod diet leads to inhibited growth rates (Dalpadado and Bogstad, 2004).

Zooplankton abundance in the Barents Sea not only depends on temperature but also on the nature of the water masses advected. Observations have suggested an inverse relationship between temperature and zooplankton abundance (Skjoldal *et al*, 1992; Tande *et al.*, 2000). However, more recent studies have pointed to a positive relationship, with the abundance of the dominant zooplankton in the Barents Sea *Calanus finmarchicus* increasing with temperature (Pershing *et al.*, 2004). Therefore, a warming trend in the Barents Sea could potentially increase this important food source for capelin (Dalpadado *et al.*, 2003), even though previous research suggests that there is no simple relationship between the temperature of the Nordic Seas and plankton biomass.

Changes in the stock development of the commercially exploited species cod and capelin inevitably have an effect on their respective fisheries. Short term economic assessments of the Barents Sea fisheries suggest that in the next few decades the choice of the correct harvesting strategy by the fishermen is of greater importance to the fate of the stocks than altered hydrographic conditions, even though warming of the Barents Sea is likely to increase biomass fluctuations (Eide, 2008). While changes in temperature patterns are generally considered in such studies, the circulation strength is considered to remain unchanged.

This study includes the aspect of changes in circulation strength and assesses the possible economic impacts of a possible weakening of the THC on the Barents Sea cod and capelin fisheries using a bioeconomic simulation model. Scenarios of climate change and THC development generated with the CLIMBER 3α model are analyzed (Montoya *et al.*, 2005). The application of actual climate change scenarios extends the analyses of Link *et al.* (2004) and Link and Tol (2006), which use hypothetical scenarios of modified productivities and/or carrying capacities to assess the economic consequences of changes in cod and capelin population dynamics. The previous studies explore sensitivities of reductions in key variables in stock dynamics for a number of economic conditions and different harvesting strategies. In the current assessment, the stock dynamics are now directly linked to scenarios of environmental change for various degrees of THC weakening, allowing inferences about the success or failure of the different harvesting strategies in case of a reduction in THC strength during this century arising from anthropogenic climate change.

The model used for the analysis and the scenarios applied are presented in the subsequent section. The results of the simulations with the model are given in section three. Finally, section four discusses the consequences that changes in the THC would have on the fisheries of the Northeast Arctic cod and Barents Sea capelin stocks.

2. Materials and methods

2.1 Model description

The bioeconomic model used in this analysis combines the short-term economic processes and population dynamics of the fish species with the long-term scenarios of environmental change. Recruitment success and survival of individual age classes are directly linked to hydrographic conditions, causing population dynamics to quickly adjust to environmental change over time. Calculations of optimal fishing efforts in each fishing period are based on stock information that is updated after each time step of the simulation. Therefore, the harvesting strategies applied are actually a series of short-term optimizations that together cover the entire long simulation period, thus bridging the gap between the different time scales of the processes covered in the model.

Two important fish species of the Barents Sea that are harvested commercially are covered: cod and capelin. Cod prey on capelin. Two different fleet types are engaged in the cod fishery: large trawlers and smaller coastal vessels. Capelin is caught mainly by purse seine vessels. Other means of catching capelin are of little importance and therefore neglected. The model assumes perfect market conditions and that the social net benefits are maximized. Both stocks are jointly managed by Norway and Russia, but we do not distinguish between fishers.

The time horizon is the 21st century. Each fishing period lasts one year. Stock size changes in each fishing period due to harvesting, natural mortality, predation and recruitment. Variables concerning the economic exploitation of the stocks and population dynamics are calculated for each fishing period. The economic development of the fisheries is assessed for two different harvesting strategies: stock size based harvesting of the fishermen and coupled stock size-hydrography based harvesting, which also considers the influence of environmental change when the fishing effort is determined. More detailed descriptions of the model are given in Link & Tol (2006) and Link *et al.* (2004).

Population dynamics of cod and capelin

Cod and capelin stocks are divided into age classes: 15 for cod and 5 for capelin. The number of individuals in each age class and the stock biomass at the beginning of a fishing period are known. Stock size is reduced by harvesting of the various fishing fleets. Stocks interact via predation with the rate of cod weight increase depending on the extent of capelin consumption. The average capelin weight-at-age is assumed constant.

Ellertsen *et al.* (1989) show that cod recruitment not only depends on spawning stock biomass but is also influenced considerably by water temperature in the spawning grounds at time of spawning. In cold years recruitment is always low whereas recruitment can be but does not have to be high in warm years since recruitment variability increases with temperature. This leads to a recruitment function that is both dependent on T and on SSB.

$$R_{cod,t} = f\left(T_t, SSB_{cod,t}\right) = \left(\rho_{cod} T_t + \sigma_{cod}\right) \varepsilon_{cod,t}\left(SSB_{cod,t}\right) \tag{1}$$

where the first terms determine the maximum possible recruitment at a given temperature and ε denotes an environmental variability term between 0 and 1 which depends on the spawning stock biomass to find the actual recruitment (Link, 2006).

Since it is not clear that capelin recruitment shows the same temperature dependence as cod recruitment, capelin recruitment is represented in the model by a Beverton-Holt functional form. However, capelin recruitment is also critically dependent on the presence of young herring in the Barents Sea (Gjøsæter and Bogstad, 1998), as recruitment either fails completely or is by far less successful in herring years. Based on the capelin recruitment data from 1973 to 1996, we assume in our simulations that capelin recruitment is reduced by 90% if herring are present. The likelihood of herring being present in a given year increases with temperature (Mikkelsen and Pedersen, 2004). Corresponding to the relationship between Barents Sea temperature and herring presence in the past decades, the probability of young herring entering the Barents Sea is set to increase stepwise from practically zero if the spring Barents Sea temperature is below 2.5°C to 50% for temperatures above 7.5°C.

The age classes at the beginning of the next fishing period consist of the surviving individuals of the next younger age class in the previous year. Cod older than 14 years accumulate in the 15+age class. As survival of cod larvae is lower for a weaker THC (Vikebø *et al.*, 2005; Vikebø *et al.*, 2007), the survival rate of cod is made independent of THC strength only for age classes 3 and older. For the youngest two age classes of cod, the survival rate is

$$\chi_{s,a,t} = 0.81 - 0.08\left(THC_{ref} - THC_t\right) \tag{2}$$

where THC_{ref} is the average THC strength near the Nordic Seas between 1990 and 2000 taken from the Climber 3α scenarios.

The fisheries

The weight of the entire catch is determined from the number of fish caught in each fishing period. The relationship between total catch and market price of fish is determined from data from previous decades and applied in the model. Therefore, fish prices are allowed to vary in relation to the amount of fish landed (Link *et al*., 2004). A fixed portion of capelin is sold for human consumption at a higher price while most of the catch is used for the production of fish meal and oil. Here, a weighted average that is slightly above the capelin price for industrial purposes is used.

Profits of each fleet reflect differences between revenues from sales of landings and the total cost of fleet operation. Total costs consist of fixed costs for fleet maintenance which are independent of fleet utilization, and variable costs directly related to the extent of fleet utilization, which is measured as a percentage of the fishing period in which the vessels are actually engaged in harvesting activities. All prices and costs are adjusted for purchasing power parity and are referenced to 1995, for which all quantities are available. As the adjusted fish prices and unit costs of harvesting have changed little during the past few decades, the unit operational costs are assumed to remain constant throughout the simulation period.

Vessels may enter or leave the fisheries depending on the economic returns in previous fishing periods. If harvesting operations of the fleets are profitable for five successive years, economic exploitation of the stock is increased, and the number of vessels rises by 1%. In contrast, if fishing operations are unprofitable, vessels are phased out to cut costs and the fleet size is reduced accordingly by 1%. The lag between profitability and change in fleet size pays tribute to the fact that the commissioning or decommissioning of vessels takes some time and involves a considerable investment. The magnitude of fleet size change roughly approximates past observations. Furthermore, technological progress causes the catchability coefficients to increase over time, more specifically; catch efficiency improves by a certain percentage each year. In reality, technological progress varies between the years, but the chosen representation is realistic in the long run.

Profits are discounted at a fixed discount rate of 7%. The control variable is the fishing effort. The economic exploitation of the stocks is limited by stock size and population dynamics of the two species.

The harvesting strategies of the fishermen

In the simulations, two different harvesting strategies are considered. One is the *stock size based fishing strategy*, an adaptive harvesting strategy in which each fleet's fishing effort is adjusted after each fishing period according to returns from fishing in the previous fishing period (Link and Tol, 2006). This is done by comparing actual catch size to a previously calculated target value of an expected harvest. Depending on whether the amount of fish landed is less (greater) than the target catch size, the fleet utilization is increased (decreased) in the following fishing period.

The other harvesting strategy is the *coupled stock size-hydrography based fishing strategy*, in which profits are maximized over a number of fishing periods that is set prior to the simulation (Link *et al*., 2004). In each fishing period, a set of fishing efforts is determined that would yield the best economic result over the specified optimization period. The optimal effort for the first fishing period is applied. After that fishing period, the actual stock developments and possible changes in hydrographic conditions are taken into consideration and the given situation is updated. Now a new set of fishing efforts is determined for a new full optimization period. This way, the result of the optimization of the coupled stock size-hydrography based harvesting strategy is not one single optimal set of fishing efforts in the long run, but a set of fishing efforts that are the initially optimal harvest activities in numerous short-term optimizations. This dynamic recursive setup has the advantage of allowing the fishermen to incorporate new information on biological and environmental developments into their strategies and update their behavior accordingly.

Two different durations of the optimization period are used in the simulations: one year and four years. An optimization period of one year is the situation in which the fishermen face the possibility that their fishing license will be withdrawn in the near future, so that only profits realized immediately are important. With a four-year optimization period, there is a reasonable certainty that fishing will continue to be allowed for some time, which makes the objective to obtain the highest possible returns for some years into the future more appropriate. Tests with optimization periods longer than four years showed results similar to the simulations optimizing over four harvesting periods. This is because discounting diminishes the importance of additional fishing periods in the optimization. Therefore, adding more fishing periods to the optimization gains little extra information and the results from simulations with a four-year optimization period can be considered characteristic for long-term coupled stock size-hydrography based harvest strategies.

Regulatory management measures to protect the stocks from overfishing are also considered: If the cod and capelin stock biomasses fall below 500 000 t or 1 000 000 t respectively, harvest activities of the respective fisheries cease. Above these thresholds, the TAC is assumed to be 35% of the stock biomass for cod and 50% for capelin. These limits are derived from the TACs set for the two species in the 1980s and 1990s.

2.2 Linking of the bioeconomic model to scenarios of environmental change

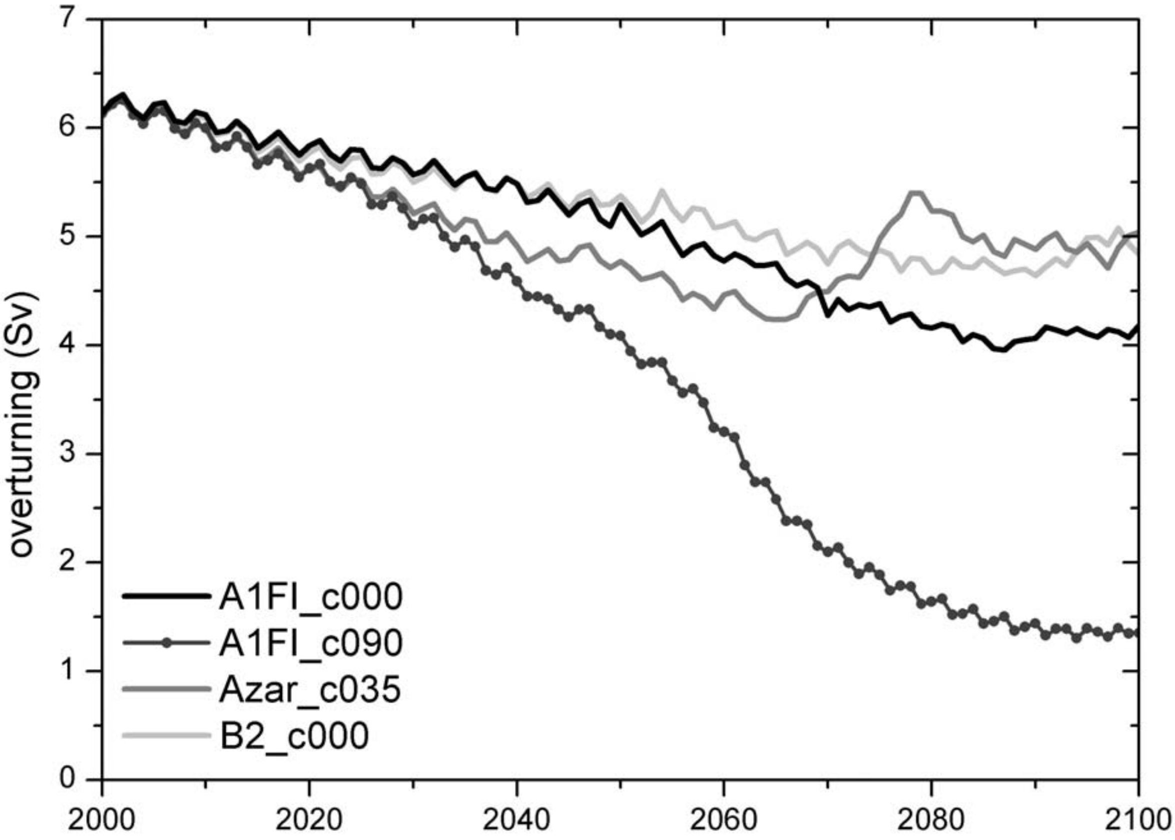

Figure 1. THC strength in the four scenarios during the 21st century.

Four different scenarios of environmental change are used in the simulations. These scenarios were generated with the Climber 3α model and describe four qualitatively different possible paths of future development of the THC and their climatological and oceanographic implications (Kuhlbrodt *et al.*, 2007). In the A1FI scenarios, CO_2 emissions are high, whereas the B2 scenario is an intermediate and Azar a low-emission scenario. Furthermore, an additional fresh water flux as a function of temperature increase is used in some scenarios, denoted by the suffix of the scenario name. In the Azar scenario, the additional flux is 0.035 Sv K^{-1}, in one A1FI scenario it is 0.09 Sv K^{-1}. In the other two scenarios, there is no flux adjustment.

The THC strength develops markedly different during the 21st century in the four scenarios. Whereas the THC weakens by less than a third and thus remains fairly stable throughout the simulation period in three scenarios, overturning decreases by 80% in the A1FI_c090 scenario, with the most pronounced change occurring in the middle of the century (Fig. 1). The change in THC strength not only has implications for the survival of fish larvae, but also on the development of the water temperature in the spawning grounds of both species during time of spawning, which is an important factor for recruitment success.

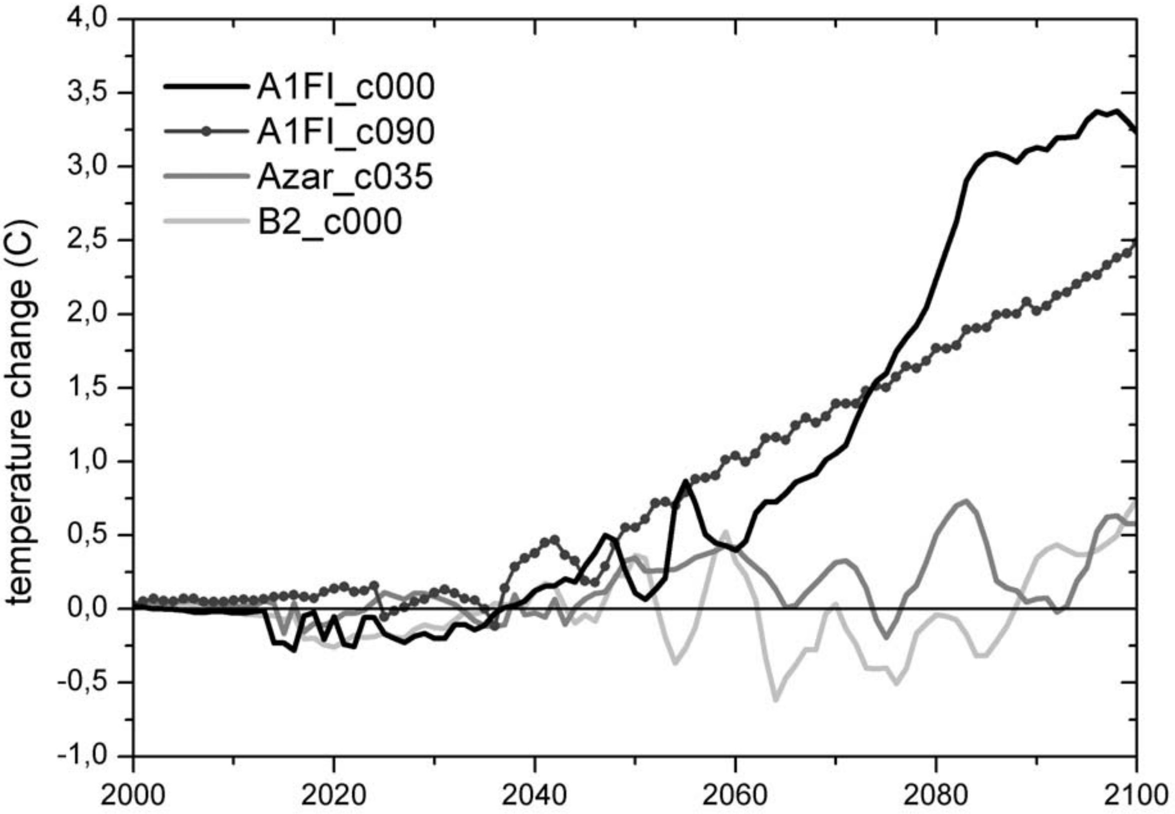

Figure 2. Change of spring temperature in the spawning grounds with respect to the 1961-1990 average.

In the model scenarios, the spring temperature in the spawning grounds of Northeast Arctic cod and capelin is determined by

(3) $$T_{sc,t} = \bar{T}_{1940-1990} + \mathrm{E}_t + \Delta T_{sc,t}$$

where the scenario temperature is based on the long-term average of measured temperatures, and the natural variability, which is assumed to remain as large throughout the simulation period as during the reference period 1940-1990. Finally, the deviation of temperatures from the initial values in the Climber 3α scenarios (Fig. 2) is added.

For the first four decades of the 21st century, all scenarios develop more or less similarly with only little deviations from the long-term average occurring. However, the temperature scenarios differ substantially in the latter half of the simulation period. The two high-emission scenarios show a large increase in temperature by 2.5 to 3.3°C by the end of the century. The temperature increase is slightly less in the scenario with a THC weakening, because temperatures in the central North Atlantic decrease as a consequence of the reduced overturning (Kuhlbrodt *et al*., 2007), thus offsetting the overall warming trend to some extent. In the other two scenarios there is no long term warming of the spawning grounds. What can be observed is that the temperature variability increases over time, with both scenarios remaining within a range of 0.5°C from the long-term average.

Since cod recruitment success improves with increasing temperature for cold water stocks such as Northeast Arctic cod (Planque and Frédou, 1999), the overall stock development is likely to be better in the A1FI scenarios. However, the negative effect of a weaker THC on stock dynamics may pose a considerable threat to the stability of the stock, particularly if the stock is exploited aggressively. For capelin, higher temperatures cause increased threats to larvae by a more frequent presence of herring and an increased predation pressure by cod (Hjermann *et al*., 2004). This may pose a substantial threat to the development of the capelin stock under altered environmental conditions, with considerable implications not only for the Barents Sea ecosystem but also to the fishery exploiting this stock.

3. Results

For each scenario, an ensemble of 100 runs was conducted for each harvesting strategy to assess the consequences of altered environmental conditions on fish population dynamics and subsequently on the fisheries exploiting the stocks. Differences between the individual runs stem from the random terms representing natural variability in the temperature and recruitment functions in the model. In both functions natural random variability is an inherent feature of reality, which can have a substantial influence on the further development of the fish stocks and their fisheries; therefore it is included in the model. The ranges of variability were approximated using the extent of observed variability from the second half of the 20th century. By means of the Monte Carlo analysis it is possible to separate the impacts of THC change from the natural variability of the system.

The initial stock sizes were obtained using the average number of individuals in each age class during the time period from 1983 to 2002 for cod (ICES, 2003a) and capelin (ICES, 2003b). The parameterizations of the simulations are given in Appendix A-3.

3.1 Impacts on fisheries using the stock size based harvesting strategy

The strength of the THC has a profound impact on the long term development of the Northeast Arctic cod stock. In the three scenarios in which the THC remains fairly stable throughout the simulation period, the cod stock biomass stays at levels above 2 million tons (Fig. 3) if fishermen follow a stock size based harvesting strategy. Differences between these scenarios are statistically not significant, suggesting that with this fishing strategy the harvest activities play a much more important role in determining the fate of the fish stock than possible changes in environmental conditions. Only in case that the THC weakens significantly, the cod stock size declines by a little about 50 per cent in the long run. This turns out to have a distinct negative impact on the fishery. Yet, the stock is never in danger of extinction. In contrast, the development of the capelin stock size is similar in all scenarios. Regardless of the fate of the THC, capelin recruitment remains at high levels, causing the stock size to remain at approximately three million tons on average throughout the simulation period. However, it needs to be noted that the variability in the development of the capelin stock is extensive and increasing in the second half of the simulation period. But even with the presence of young herring frequently reducing the number of capelin offspring, the probability of complete stock failure is negligible.

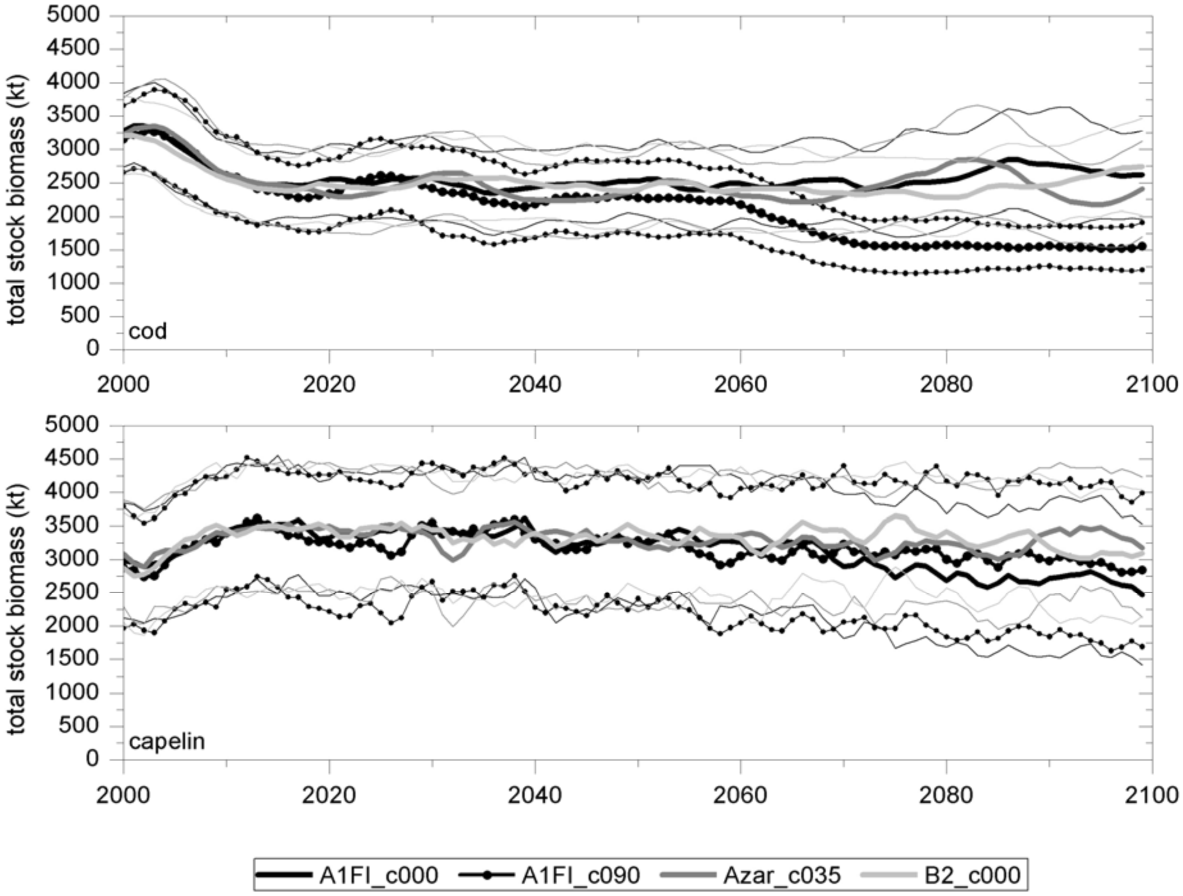

Figure 3. Development of the stock biomasses if fishermen employ stock size based harvesting strategies. Thick lines denote the average of the 100 runs in each ensemble, thin lines the corresponding standard deviations.

In three of the four scenarios analyzed, average annual cod catches remain fairly stable throughout the simulation period at a level of approximately 400 000 to 600 000 tons. The differences between the three scenarios with a stable THC are small and statistically not significant (Fig. 4), even though the variability in harvest success increases somewhat over time. Only in the A1FI_c090 scenario with a strong THC weakening a very strong decline in cod catches can be observed: by the end of the century, total cod landings barely exceed 100 000 tons per year, not enough to maintain the fishery at a viable level. Furthermore, it has to be noted that the importance of coastal vessels for the cod fishery declines over time in all four scenarios if this harvest strategy is employed, leading to a distinct reduction in fleet size (Tab. 1).

On average, the capelin fishery maintains fairly high catch levels throughout the simulation period. Annual catches fluctuate around 800 000 tons (Fig. 4) and are similar in all scenarios. Slightly increasing or decreasing trends are consequences of changes in predation pressure rather than impacts of environmental change. Even a reduction in THC strength has little influence on this fishery. However, the apparent stability of the fishery is an inherent feature of the data aggregation of the results, which masks the existing high variability in capelin catches that may appear in individual simulation runs.

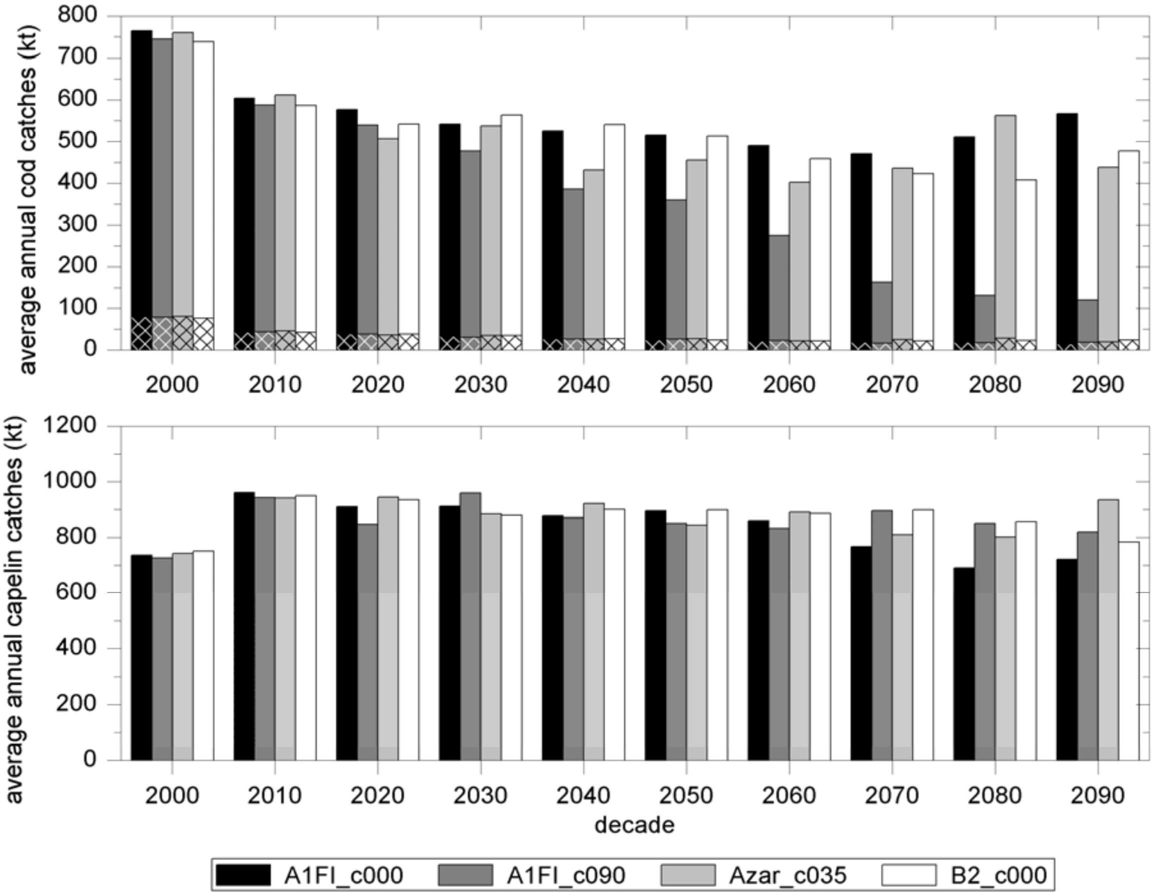

Figure 4. Average annual catches of all fleets in each decade if stock size based harvesting strategies are used. Cod catches: regular columns denote trawl catches, shaded columns catches by coastal vessels.

The net present values of profits of the three fleet types develop quite differently in the four scenarios analyzed (Tab. 1). In the cod fishery, average annual profits decline over time in all scenarios, owing to the large overall profits in the first three decades of the simulations. While the increased variability leads to some good economic results towards the end of the century in the Azar_c035 scenario, the trawl fishery becomes unprofitable in the A1FI_c090 scenario. Not even a contraction of the fleet size improves the profitability of the cod fishery in that scenario.

Profits of coastal vessels are negative in all scenarios throughout the simulation period and not even a large reduction in the number of vessels causes costs to decline enough for the fleet to become profitable (Fig. 4). The bad economic result has to do with the fact that most of the total allowable catch (TAC) in each fishing period is allotted to the more efficient trawlers, causing trawl profits to be particularly high. However, the remaining portion of the TAC is not large enough to cover all costs of the coastal vessel fleet. The number of vessels decreases considerably in all scenarios but this cost reduction in the model is too slow to finally make the coastal vessel fleet become profitable. This shows that the stock size based harvesting strategy used is unsuitable for the small coastal vessels.

The exploitation of the capelin stock using purse seiners has quite substantial economic significance if the stock size based harvesting strategy is used, owing to the fairly large standing stock biomass, which follows from the use of the Beverton-Holt type recruitment function (Fig. 4). The profitability of the capelin fishery follows the same pattern as the catches, with only marginal differences occurring between the various scenarios (Tab. 1).

The fleet size increases considerably over time in all scenarios, as the profits per vessel remain distinctly positive despite an expansion of fleet size.

	A1FI_c000		A1FI_c090		Azar_c035		B2_c000	
	average annual profit [million Nkr]	average fleet size [no. of vessels]	average annual profit [million Nkr]	average fleet size [no. of vessels]	average annual profit [million Nkr]	average fleet size [no. of vessels]	average annual profit [million Nkr]	average fleet size [no. of vessels]
trawlers								
2000s	3523.98	70	3454.71	69	3495.74	70	3422.61	70
2010s	2616.06	84	2497.73	83	2622.52	83	2525.30	84
2020s	2284.21	104	2103.31	102	1888.42	102	2079.88	103
2030s	1791.13	123	1441.67	121	1802.04	121	1954.69	122
2040s	1458.17	145	717.96	137	943.66	141	1495.68	145
2050s	1104.22	165	385.45	148	913.48	155	1099.63	164
2060s	778.80	180	-277.42	150	373.33	168	607.69	178
2070s	464.42	191	-928.49	137	598.11	171	284.45	186
2080s	610.86	198	-827.96	116	1095.38	183	160.40	188
2090s	686.54	209	-640.30	97	148.73	196	553.71	192
coastal vessels								
2000s	4.29	465	9.30	465	15.31	465	-7.92	464
2010s	-205.42	443	-206.14	446	-196.17	449	-192.26	441
2020s	-119.19	397	-111.56	397	-127.81	400	-112.69	397
2030s	-109.03	362	-105.93	361	-86.43	366	-89.30	364
2040s	-101.20	327	-59.43	326	-93.44	335	-112.32	333
2050s	-90.92	295	-40.53	303	-48.37	305	-90.81	297
2060s	-78.67	267	-51.24	285	-68.97	284	-58.93	267
2070s	-70.52	241	-72.56	261	-22.15	261	-30.24	248
2080s	-58.33	218	-39.06	234	-21.20	251	-13.59	235
2090s	-89.36	198	-18.96	220	-62.60	236	-10.16	227
purse seiners								
2000s	666.92	84	655.59	83	675.10	84	683.81	84
2010s	916.59	100	897.92	99	896.66	100	904.43	100
2020s	839.96	116	769.39	116	883.59	117	873.31	117
2030s	829.11	133	888.67	132	794.70	133	788.24	133
2040s	776.59	148	766.65	148	830.43	149	797.68	149
2050s	787.50	162	736.74	162	720.66	163	785.58	164
2060s	731.82	174	707.10	173	767.07	176	752.54	177
2070s	620.42	185	772.77	186	659.04	189	758.49	192
2080s	538.53	193	723.94	198	646.33	201	691.49	210
2090s	580.58	201	682.29	209	788.78	213	598.75	226

Table 1: average annual profits and fleet sizes in each decade if a stock size based harvesting strategy is employed

3.2 Impacts on fisheries using coupled stock size-hydrography based management

Simulations were conducted with optimization periods of one year and four years. The following assessment focuses mainly on the simulations with an optimization period of four years since the fisheries of cod and capelin in the Barents Sea are initially not in danger of being closed permanently and thus a harvesting strategy of the fishermen that encompasses not only the present is deemed appropriate.

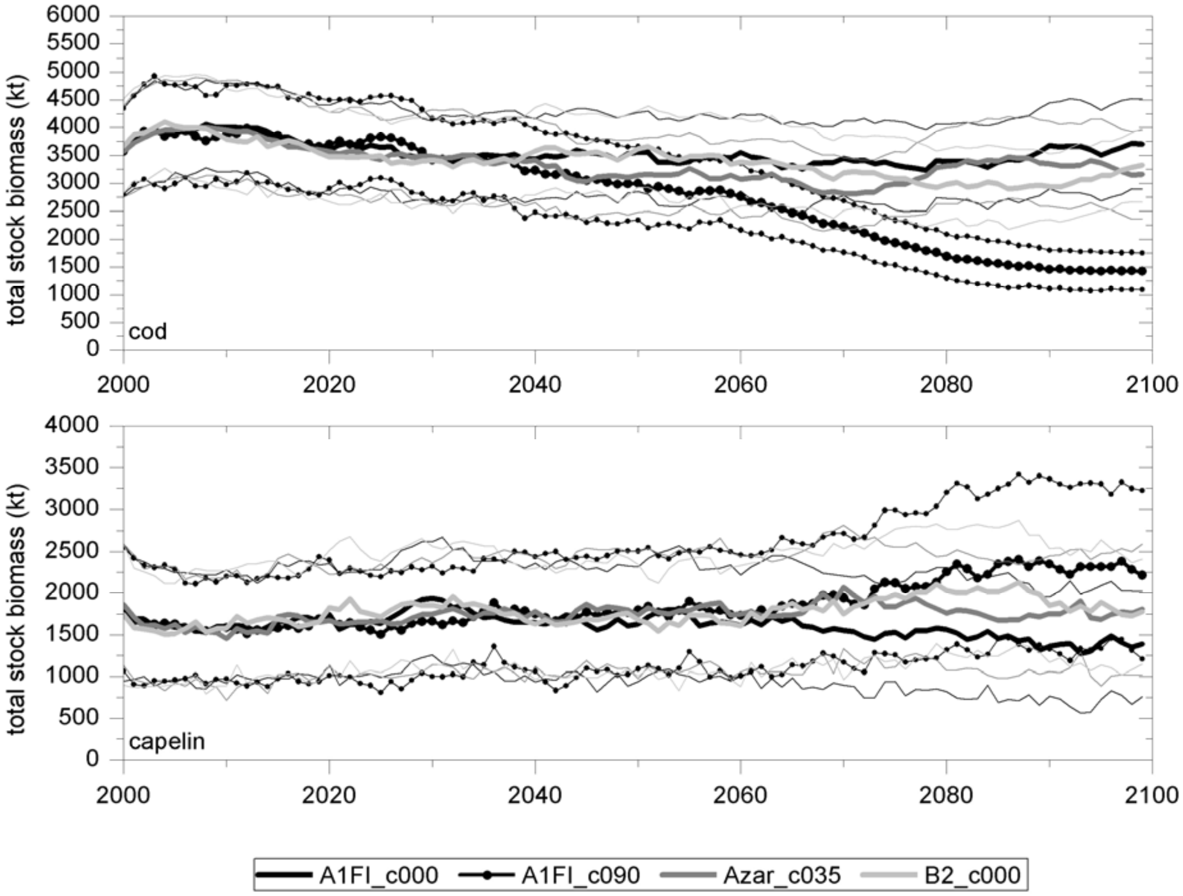

Figure 5. Development of the stock biomasses if fishermen employ coupled stock size-hydrography based strategies. Thick lines denote the average of the 100 runs in each ensemble, thin lines the corresponding standard deviations.

In all scenarios, the cod stock qualitatively develops similarly with a coupled stock size-hydrography based fishing strategy as with purely stock size based harvesting. However, the A1FI_c090 scenario produces a more pronounced decline in standing stock biomass if the coupled stock size-hydrography based strategy is applied. While a stable THC is beneficial for the stock to the extent that the average stock size reaches at least three million tons of biomass by the end of the simulation period, the negative influence by the weakened THC causes the stock to decline to only a little more than 1 million tons in the A1FI_c090 scenario (Fig. 5). The differences between the three scenarios without a THC shutdown are rather insignificant, but there is a marginal increase in variability of stock size in the latter half of the simulation period.

On average, the capelin stock biomass is influenced little by changes in environmental conditions. Because of the harvesting strategy that allows for fishing periods in which catches are deferred to the future, the stock can be kept from being in danger of extinction in all scenarios (Fig. 5). In the A1FI_c090 scenario, the stock benefits from the reduced number of cod to increase in size despite a more frequent presence of herring preying on young capelin. However, this effect occurs only in the last few decades of the simulation period and does not lead to a significantly higher stock level. The variability of the capelin stock size also increases with time in all scenarios, owing to the larger variability in environmental conditions, but the stock generally stays away from critically low biomass levels, to allow a steady exploitation of the stock.

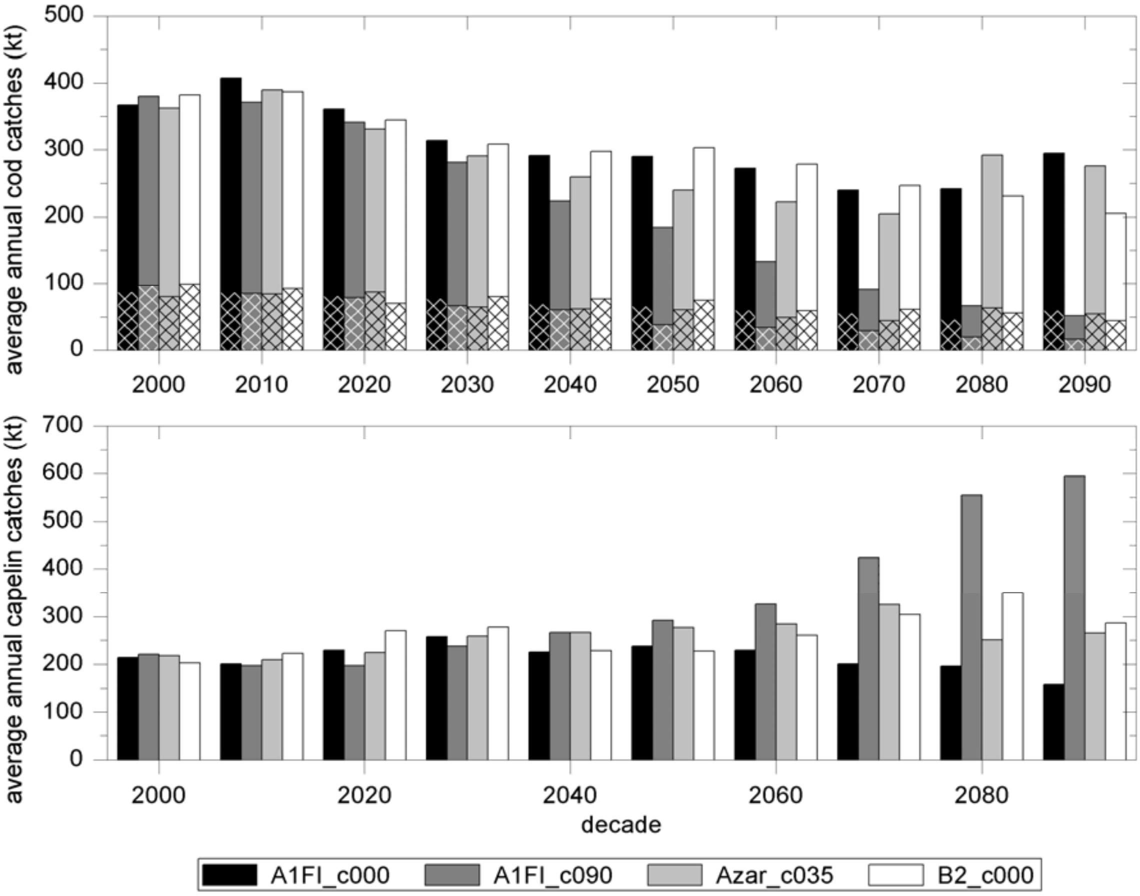

Figure 6. Average annual catches of all fleets in each decade if a coupled stock size-hydrography based fishing strategy is used. Cod catches: regular columns denote trawl catches, shaded columns catches by coastal vessels.

Cod catches show a similar pattern for both the coupled stock size-hydrography based fishing strategy and stock size based harvesting, but with the former strategy the overall average catch sizes are distinctly lower (Fig. 6), resulting in a larger standing stock biomass. This is because the optimization period of four years allows the fishermen to postpone catches in some years to allow further growth of the resource. Catch levels of coastal vessels are higher, which underscores their greater importance if this harvesting strategy is applied. The difference in total landings, however, is mainly attributable to reduced trawl catches.

Average annual capelin catches are similar in three of the four scenarios, with landings amounting to 200 000 to 350 000 tons per year throughout the simulation period. Only in the A1FI_c090 scenario, the capelin fishery can benefit from the generally larger stock size in the last few decades of the simulation period, leading to a point at which catches are more than twice as large as at the beginning of the century (Fig. 6). In all scenarios, capelin catches are substantially lower with a coupled stock size-hydrography based harvest strategy, as the fishery has to deal with a substantial influence of predation on the stock by cod and by herring feeding on the capelin larvae, causing much lower TACs to be set than for stock size based harvesting, thus inhibiting the economic exploitation of the stock to a large extent.

Compared to stock size based harvesting, profits from fishing are distributed quite differently among fleets when the coupled stock size-hydrography based strategies are used by the fishermen. Except for the A1FI_c090 scenario, in which the overall profitability of the cod fishery becomes negative in the last few decades of the simulation period, the average annual profits of all fleets are positive throughout the 21st century (Tab. 2). With the coupled stock size-hydrography based fishing strategy, profits are spread more evenly among trawlers and coastal vessels, causing the coastal vessel fleet to shrink much less than with stock size based harvesting. On the other hand, the number of trawlers declines slightly instead of increasing strongly over time. In all scenarios, there is a general trend of high profits at the beginning of the simulation period decreasing with time and recovering to some extent at the end of the century. For the cod fishery, the range of fluctuation is much less if the coupled stock size-hydrography based harvesting strategy is applied than with stock size based harvesting, which reduces the operational risks of the fishery. The profitability of the capelin fishery is much smaller if the coupled stock size-hydrography based approach is used by the fishermen as the amount of fish that may be caught each fishing period is much smaller than for the other fishing strategy. Consequently, the expansion of the fleet engaged in this fishery is quite moderate and profits take a large hike only in the scenario that features a strong reduction on predator biomass, leaving more capelin to be harvested. But apart from this scenario, the economic importance of the capelin fishery remains far behind the cod fishery despite its expansion throughout the simulation period.

	A1FI_c000		A1FI_c090		Azar_c035		B2_c000	
	average annual profit [million Nkr]	average fleet size [no. of vessels]	average annual profit [million Nkr]	average fleet size [no. of vessels]	average annual profit [million Nkr]	average fleet size [no. of vessels]	average annual profit [million Nkr]	average fleet size [no. of vessels]
trawlers								
2000s	1750.40	58	1785.06	58	1798.56	58	1802.23	58
2010s	2258.79	57	1893.61	57	2094.39	57	1939.10	56
2020s	1838.35	56	1749.32	56	1503.44	56	1792.97	55
2030s	1457.80	55	1242.38	54	1397.52	54	1402.66	54
2040s	1319.09	54	798.78	52	1141.88	53	1374.22	53
2050s	1422.00	52	691.84	50	970.54	51	1468.63	51
2060s	1294.48	51	277.58	47	981.01	48	1372.53	49
2070s	1118.69	49	-38.57	43	880.17	46	1079.78	47
2080s	1239.89	46	-130.09	38	1596.96	44	1047.17	46
2090s	1655.64	44	-166.92	34	1550.61	43	921.97	43
coastal vessels								
2000s	521.33	463	625.57	461	438.96	458	609.52	459
2010s	556.76	433	519.91	430	517.03	426	594.67	430
2020s	513.00	406	506.88	402	581.33	397	390.62	401
2030s	488.12	379	403.56	374	376.91	372	522.06	377
2040s	422.24	355	357.30	348	390.06	344	518.65	354
2050s	428.82	329	163.36	323	379.06	319	514.03	331
2060s	396.07	305	140.68	295	288.52	294	353.84	309
2070s	369.80	284	107.20	268	251.31	269	405.03	288
2080s	284.82	262	29.18	244	460.78	251	374.47	268
2090s	440.78	242	6.64	221	379.38	234	273.12	249
purse seiners								
2000s	143.44	75	148.02	76	146.48	76	132.85	75
2010s	127.17	79	123.72	79	136.20	80	147.79	79
2020s	153.79	82	124.61	82	147.63	84	193.95	83
2030s	181.02	88	161.20	86	181.56	89	199.70	89
2040s	149.53	93	190.97	90	187.26	93	150.16	95
2050s	160.57	97	212.37	94	197.81	98	148.59	100
2060s	151.78	101	245.20	99	202.57	103	178.52	104
2070s	124.00	104	343.09	102	242.90	108	223.55	110
2080s	121.43	105	480.35	109	167.02	114	264.33	119
2090s	86.86	105	518.29	119	181.21	120	198.25	128

Table 2: average annual profits and fleet sizes in each decade if a coupled stock size-hydrography based strategy is employed

The above analysis is based on results from a strategy that maximizes profits over four consecutive harvesting periods. If fishermen attempt to maximize profits only in the current fishing period while disregarding any future development, results are considerably different: harvesting of cod is initially greater, so the overall biomass level tends to be lower. With the average cod stock size fluctuating around 1 million tons in all scenarios, a change in THC strength has a much more pronounced impact on the fisheries than if the stocks had been exploited more conservatively prior to the change in environmental conditions. As the cod fishery already operates with little profitability in the first few decades of the simulation period, the fishery breaks down completely if the development of the cod stock is influenced negatively by external effects. Even though capelin landings are higher due to generally larger capelin abundance than in the scenarios discussed above, the increased profitability of the capelin fishery is insufficient to compensate for the much worse economic returns incurred by the cod fishery.

Discussion

In this paper, we present estimates of the consequences of a severe weakening of the THC for the cod and capelin fisheries in the Barents Sea. It has to be noted that this assessment of the impacts of a THC collapse is based on the assumption that despite the changes in temperature and circulation patterns addressed the overall structure of the Barents Sea ecosystem remains intact. Complete failures of food sources of the two species would have implications on the stocks that cannot be represented in the model. The same holds for the structures of the fisheries. Drastic changes in the means of economic exploitation of the marine resources are disregarded and it is assumed that the current system of quota-regulated fisheries remains in place throughout the simulation period. Therefore, the results presented in this paper are by no means to be considered as concrete predictions of economic impacts of a THC breakdown on the fisheries. Instead, they should rather be viewed as indicators of the possible trends induced by a weaker THC and estimates of their general magnitude, for which the emerging patterns are of greater importance than the actual absolute values.

The simulations show that there are two effects influencing the development of the fish stocks that have opposite consequences: warming of the spawning grounds due to anthropogenically induced climate change improves chances of strong recruitment year classes, which leads to increased stock sizes. On the other hand, the survival rates of particularly cod larvae and the youngest age classes depend on a circulation pattern that transports them from the spawning grounds into the Barents Sea and does not let them end up West of Svalbard, far away from feeding grounds (Vikebø *et al.*, 2007). In case of a THC weakening, this phenomenon worsens the prospects of successful stock development. A comparison of the two A1FI scenarios reveals that the latter effect has a substantial impact on the cod stock, which is 40% (stock size based harvesting) to 65% (coupled stock size-hydrography based harvesting) smaller by the end of the simulation period if the THC weakens. The similar development of the cod stock in the three scenarios with an intact THC shows that, in contrast, the stimulating impact of a temperature increase in the spawning grounds on the population dynamics is rather limited, at least for the magnitude of temperature change considered in this assessment.

Since a temperature dependence of capelin recruitment is not supported by current research, a Beverton-Holt type recruitment function was used for capelin, while the dependence of cod recruitment on spawning temperature is explicitly included. This however, leads to a relative overestimation of capelin recruitment, which becomes apparent in the simulations using stock size based harvesting, in which the economic importance of the capelin fishery is somewhat overemphasized in comparison with the cod fishery.

An important factor influencing capelin stock development is the presence of young herring, whose probability of migrating to the Barents Sea to feed on capelin larvae increases with warmer conditions in the Barents Sea. The presence of herring poses a threat to the survival of the capelin stock if the overall stock biomass is below a threshold of approximately 1 million tons, which is, however, rarely the case in the simulations. Consequently, the capelin stock is generally large enough to withstand an occasionally occurring drastic reduction in recruitment success. Furthermore, the capelin stock can benefit from reduced predation pressure due to the declining cod stock size in the THC weakening scenario, which benefits the capelin fishery, leading to the highest returns in the A1FI_c090 scenario regardless of the harvesting strategy chosen.

Catches of both species follow similar general patterns that are independent of the harvest strategy chosen: cod landings start out at a high level that cannot be exceeded throughout the remainder of the simulation period. The largest catches can be obtained under conditions without the THC breaking down. The cod fishery remains viable despite increased natural variability in the scenarios with an intact THC, despite the higher economic risks involved in exploiting a stock with a more fluctuating biomass. Only if the THC weakens to such an extent that recruitment success is impaired on a regular basis, the stock size drops to levels that do not allow for profitable exploitation at the end of the simulation period anymore.

However, there are distinct differences in the distribution of market shares between the two harvesting strategies: the stock size based harvesting strategy clearly favors the trawl fleet while catches by coastal vessels are too small to profitably operate the fleet. The consequence is a clear reduction in fleet size while there is a simultaneous expansion of the trawl fleet. In contrast, coastal vessels remain a more important part of the cod fishery if the coupled stock size-hydrography based harvesting strategy is used. Here, the number of coastal vessels is also reduced over time but to a much lesser extent, as the trawl fleet remains only stable in size and does not expand. Considering the fact that there are substantial costs involved in building and wrecking of vessels which are not yet considered in these simulations, the coupled stock size-hydrography based harvesting strategy leads to much more stability in the cod fishery than the stock size based strategy.

Capelin catches are similar in all scenarios during the first half of the simulation period, when any hydrographic change is still small. The long-term development of the capelin fishery depends on the harvest strategy applied. For stock size based harvesting, the capelin stock is generally large enough so that stable economic exploitation can be sustained regardless of the development of the hydrographic conditions. But with smaller overall catch levels, the influence of changes in THC strength becomes more apparent in later fishing periods. For a weaker THC the capelin fishery can benefit from strongly increasing amounts of capelin landed in the A1FI_c090 scenario, since the capelin fishery can harvest the additional capelin that does not fall prey to cod due to the reduced number of predators left. This helps the capelin fishery gain the highest returns regardless of the harvest strategy employed.

Overall profits from fishing are initially higher with stock size based harvesting strategies than with the coupled stock size-hydrography based approach, even though the large returns only stem from the trawl fishery, while coastal vessels operate below or close to their break even points. It can hardly be desirable to have one part of the fishery system practically subsidize the other fleets. Profits from coupled stock size-hydrography based harvesting with an optimization period of several years are much more stable over time with all fleets contributing to the profitability of the Barents Sea fishery system. Particularly during the second half of the simulation period, when environmental variability (Azar_c035 and B2_c000 scenarios) and the deviation from initial conditions are largest (A1FI scenarios), the combined total profits of all fleets exceed those accrued with stock size based harvesting. Also, a coupled stock size-hydrography based strategy with a longer optimization period yields superior results than a short-term focus when harvesting is greater during the first decades of the simulation period. This leads to lower standing stock biomasses, which puts the stock development at risk in times of increasing environmental variability. Consequently, profits diminish in the long run in comparison to a more forward-looking harvest strategy.

All harvest strategies yield a positive total profit of all fleets as long as the THC remains intact or weakens by only a third, as is the case in three of the four scenarios assessed. If, however, the THC weakens much more or breaks down completely, none of the strategies analyzed was able to keep the fisheries profitable in the long run. This is particularly true for the cod fishery, which suffers most when population dynamics are negatively affected by changes in the circulation pattern. The capelin fishery gains in economic importance but due to the lower unit price of the species it is not possible to offset the losses of the cod fishery. The results of this assessment suggest that a more flexible harvest strategy than pure profit maximization or adaptation based on simple rules is needed to effectively deal with the situation of impaired stock development of Northeast Arctic cod and capelin in the Barents Sea region caused by changes in THC strength.

It has to be noted, however, that while the simulation model already encompasses many features of the Barents Sea fisheries and the interactions between the exploited species, some aspects are still disregarded in the model, which may influence the development in the different scenarios: besides the two species themselves, their main food sources are also affected by changes in hydrographic conditions. The model assumes that food availability, which is an important factor influencing the survival rate of the individual age classes remain unchanged throughout the simulation period. Changes in food availability may also trigger shifts in the range of the two species, which in turn can have an influence on the fisheries, as distances from ports to fishing grounds change with the species ranges. Also, the harvest strategy applied does not change throughout the simulation period. Returns from fishing might increase if it was possible to switch between different harvesting strategies within the simulations.

Despite the simplifications embodied in our simulation model, it is possible to obtain some insights about the possible consequences of a reduction in THC strength on the cod and capelin stocks in the Barents Sea and the catches of their respective fisheries under a simple stock size based and a coupled stock size-hydrography based harvesting strategy. Incorporation of additional food web interactions and more sophisticated harvest strategies are the scope of further assessments with this model to explore the economic impacts of changes in circulation patterns on the Nordic Seas fisheries.

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Appendix A.

Table A-1.List of symbols used in the model equations.

symbol	**meaning**
a	index denoting the age class
cap	index referring to capelin
cod	index referring to cod
e	fleet utilization
g	rate of reproduction
h	harvest
harv	index denoting the stock size after harvesting has been considered
hum	index referring to the share of human consumption of capelin
i	index denoting the fleet type
ind	index referring to industrial use
init	index referring to the beginning of a fishing period
m	spawning weight of the adult fish
n	number of individuals in an age class
pred	index denoting the stock size after harvesting and predation have been considered
q	catchability coefficient
r	revenue
s	index denoting the species
t	index denoting the fishing period
v	number of vessels
w	weight
A	highest age class of a species
B	stock biomass
D	prey density
G	expected growth of the stock
K	carrying capacity
P	fish price
R	recruitment
SSB	spawning stock biomass
T	temperature
THC	strength of the thermohaline circulation
α	parameter used in capelin recruitment function
β	parameter used in capelin recruitment function
γ	exponent in function determining the prey density
δ	discount rate
ε	environmental variability term used in cod recruitment function
ζ	reference price of fish
η	unit price of fish
θ	variable costs of fishing
ι	parameter used in calculation of predated biomass
κ	rate of predation
λ	learning factor
μ	share of mature individuals
π	profit per fishing period
ρ	parameter used in function relating cod recruitment to spawning temperature
σ	parameter used in function relating cod recruitment to spawning temperature
τ	length of the optimization period
φ	fixed costs
χ	natural survival rate
ψ	total costs
E	natural variability of temperature in cod and capelin spawning grounds
Θ	cost per unit effort
Π	net present value of profits over a period of τ years

Table A-2. Summary of model equations. See Table A-1 for symbols.

population dynamics of the fish species	exploitation of the stocks
(A1) $B^{init}_{s,t} = \sum_a w_{s,a,t} n^{init}_{s,a,t}$	(A10) $h_{s,i,a,t} = q_{s,i,a,t} n^{init}_{s,a,t} v_{s,i} e_{s,i,t}$
(A2) $n^{harv}_{s,a,t} = n^{init}_{s,a,t} - \sum_i h_{s,i,a,t}$	(A11) $P_{s,i,t} = \xi + \eta \sum_{s,a} h_{s,i,a,t} w_{s,a,t}$
(A3) $SSB_{s,t} = \sum_a \mu_{s,a} m_{s,a} n^{harv}_{s,a,t}$	(A12) $r_{i,t} = \sum_{s,a} P_{s,i,t} h_{s,i,a,t} w_{s,a,t}$
(A4) $\chi_{s,a,t} = 0.81 - 0.08\left(THC_{ref} - THC_t\right)$	(A13) $\psi_{s,i,t} = \varphi_{s,i} + e_{s,i,t}\theta_{s,i}$
(A5a) $R_{cod,t} = \left(\rho_{cod} T_t + \sigma_{cod}\right)\varepsilon_{cod,t}\left(SSB_{cod,t}\right)$	(A14) $\pi_{i,t} = r_{i,t} - v_i \psi_{i,t}$
(A5b) $R_{cap,t} = g_{cap,t} \frac{\alpha_{cap,t} SSB_{cap,t}}{\left(1 + \beta_{cap,t} SSB_{cap,t}\right)}$	
$n^{init}_{s,1,t+1} = R_{s,t}$	
(A6) $n^{init}_{s,a+1,t+1} = \chi_{s,a,t} n^{harv/pred}_{s,a,t}$	
$n^{init}_{cod,A,t+1} = \chi_{cod,A,t} n^{harv}_{cod,A,t} + \chi_{cod,A-1,t} n^{harv}_{cod,A-1,t}$	
	(A15) $\Pi_i = \sum_{t=t_0}^{t_0+\tau} e^{-\delta(t-t_0)} \pi_{i,t}$
predation and weight increase	stock size based harvesting strategies
(A7) $D_{cap,t} = \frac{D^{\max}_{cap}}{1 + \left(D^{\max}_{cap} - 1\right)\left(\frac{B^{harv}_{cap,t}}{B^{std}_{cap}}\right)^{-\gamma}}$	(A16) $G^{\exp}_{s,t}\left(B^{init}_{s,t}\right) = g^{\exp}_{s,t} B^{init}_{s,t}\left(1 - \frac{B^{init}_{s,t}}{K_{s,t}}\right)$
(A8) $B^{pred}_{cap,t} = \kappa D_{cap,t} B^{harv}_{cod,t}$	(A17) $\Theta_{s,i,t} = \frac{\psi_{s,i,t}}{\bar{q}_{s,i,a,t} B^{init}_{s,t}}$
(A9) $w_{cod,a+1,t+1} = w_{cod,a,t} + \widehat{w}_{cod,a}\left(D_{cap,t}\iota + \left(1 - \iota\right)\right)$	(A18) $G'^{\exp}_{s,i,t} - \frac{\Theta'_{s,i,t} G^{\exp}_{s,i,t}}{P_{s,i} - \Theta_{s,i,t}} = \delta$
	(A19) $e_{s,i,t+1} = \frac{g^{\exp}_{s,t}}{q_{s,i} v_i}\left(1 - \frac{B^{*}_{s,t}}{K_{s,t}}\right)$
	(A20) $\bar{g}_{s,t} = \frac{B^{init}_{s,t} - B^{init}_{s,t-1}}{B^{init}_{s,t-1}}$
	(A21) $g^{\exp}_{s,t+1} = \lambda_s \bar{g}_{s,t} + \left(1 - \lambda_s\right) g^{\exp}_{s,t}$

Table A-3. Summary of parameters and initial values used in the simulations.

Parameter	**value**	**source**
population dynamics of capelin		
initial number of individuals in each age group $n_{cap,a,0}$	[2.16e+11 1.70e+11 5.64e+10 9.97e+09 0.73e+09]	based on ICES (2003b)
mean weight in each age group $w_{cap,a}$	[0.0036 0.0102 0.0182 0.024 0.0265] kg	based on ICES (2003b)
proportion of mature individuals $\mu_{cap,a}$	[0.00 0.01 0.41 0.87 1.00]	based on ICES (1999)
mean spawning weight per age class $m_{cap,a}$	[0.00324 0.00918 0.01638 0.0216 0.02385] kg	calculated from mean weight-at-age
initial survival rate $\chi_{cap,a,0}$	0.535	adapted from Sumaila (1997)
carrying capacity K_{cap}	8 million tons	set to be consistent with observations
population dynamics of cod		
initial number of individuals in each age group $n_{cod,a,0}$	[9.82e+08 2.91e+08 1.78e+08 1.17e+08 7.31e+07 3.59e+07 1.25e+07 3.4e+06 8.0e+05 4.0e+05 2.6e+05 1.12e+05 4.8e+04 2.1e+04 9.0e+03]	based on ICES (2003a)
initial mean weight in each age group $w_{cod,a,0}$	[0.104 0.42 0.85 1.30 1.89 2.73 3.87 5.28 6.87 8.33 10.10 12.36 12.72 13.60 16.71] kg	based on ICES (2003a)
proportion of mature individuals $\mu_{cod,a}$	[0 0 0.02 0.023 0.08 0.315 0.591 0.787 0.891 0.973 0.99 1.0 1.0 1.0 1.0]	based on ICES (2003a)
initial mean spawning weight per age class $m_{cod,a,0}$	[0.094 0.378 0.765 1.170 1.701 2.457 3.483 4.572 6.183 7.497 9.090 11.124 11.448 12.240 15.039] kg	calculated from mean weight-at-age data
parameter used in recruitment function ρ_{cod}	390	own calculations based on Ellertsen *et al*. (1989)
parameter used in recruitment function σ_{cod}	520	own calculations based on Ellertsen *et al*. (1989)
initial survival rate $\chi_{cod,a,0}$	0.81	adapted from Sumaila (1997)
carrying capacity K_{cod}	6 million tons	set to be consistent with observations
parameters relating to the predator-prey-relationship		
maximum value of $D_{cap,t}$: $D_{cap,max}$	1.5	Moxnes (1992)
standard biomass of capelin $B_{cap,std}$	4.467 million t	Moxnes (1992)
rate of weight increase of cod $\hat{w}_{cod,a}$	[0.25 0.33 0.35 0.46 0.65 0.88 1.09 1.23 1.13 1.37 1.75 0.28 0.68 2.41 0.10] kg	set to be consistent with initial values of weight-at-age data

rate of predation κ	1.235	Moxnes (1992)
influence of predation on weight of cod ι	0.6	Moxnes (1992)
economic parameters of trawlers		
initial fleet size $v_{TR,0}$	60	adapted from Statistisk Sentralbyrå (2002)
initial catchability coefficient $q_{TR,0}$	0.0074	Sumaila (1995)
fixed costs φ_{TR}	15.12 million Nkr	Sumaila (1995)
variable costs θ_{TR}	12.88 million Nkr	Sumaila (1995)
economic parameters of coastal vessels		
initial fleet size $v_{CV,0}$	500	adapted from Statistisk Sentralbyrå (2002)
initial catchability coefficient $q_{CV,0}$	0.00593	Sumaila (1995)
fixed costs φ_{CV}	0.65 million Nkr	Sumaila (1995)
variable costs θ_{CV}	0.88 million Nkr	Sumaila (1995)
economic parameters of purse seine vessels		
initial fleet size $v_{PS,0}$	70	adapted from Statistisk Sentralbyrå (2002)
initial catchability coefficient $q_{PS,0}$	0.0175	adapted from Sumaila (1997)
fixed costs φ_{PS}	0.42 million Nkr	adapted from Sumaila (1997)
variable costs θ_{PS}	0.58 million Nkr	adapted from Sumaila (1997)
general economic parameters		
reference price for cod $\zeta_{cod,ref}$	10.77 Nkr /kg	own calculation based on observed data
reference price for industrially used capelin $\zeta_{cap,ind,ref}$	0.86 Nkr / kg	own calculation based on observed data
reference price for capelin for human consumption $\zeta_{cap.hum,ref}$	4.20 Nkr / kg	own calculation based on observed data
discount rate δ	0.07	set to be consistent with common practice
learning factor λ_s	0.5 for all fleets	

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