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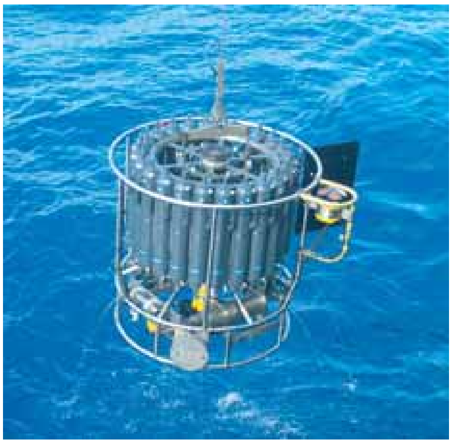
Modeling the economic impacts of changes in thermohaline circulation with an emphasis on the Barents Sea fisheries

Peter Michael Link



Berichte zur Erdsystemforschung 33/2006

Reports on Earth System Science

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Layout:

Bettina Diallo, PR & Grafik

Titelfotos:
vorne:
Christian Klepp - Jochem Marotzke - Christian Klepp
hinten:
Clotilde Dubois - Christian Klepp - Katsumasa Tanaka

Berichte zur Erdsystemforschung

33
2006

Modeling the economic impacts of changes in thermohaline circulation with an emphasis on the Barents Sea fisheries

Dissertation zur Erlangung des Doktorgrades der Naturwissenschaften
im Departement Geowissenschaften der Universität Hamburg
vorgelegt von

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aus San Francisco, CA (USA)

Hamburg 2006

Reports on Earth System Science

33
2006

ISSN 1614-1199

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Als Dissertation angenommen
vom Departement Geowissenschaften der Universität Hamburg

auf Grund der Gutachten von
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Hamburg, den 28. November 2006
Prof. Dr. Kay-Christian Emeis
Leiter des Departements für Geowissenschaften

ISSN 1614-1199

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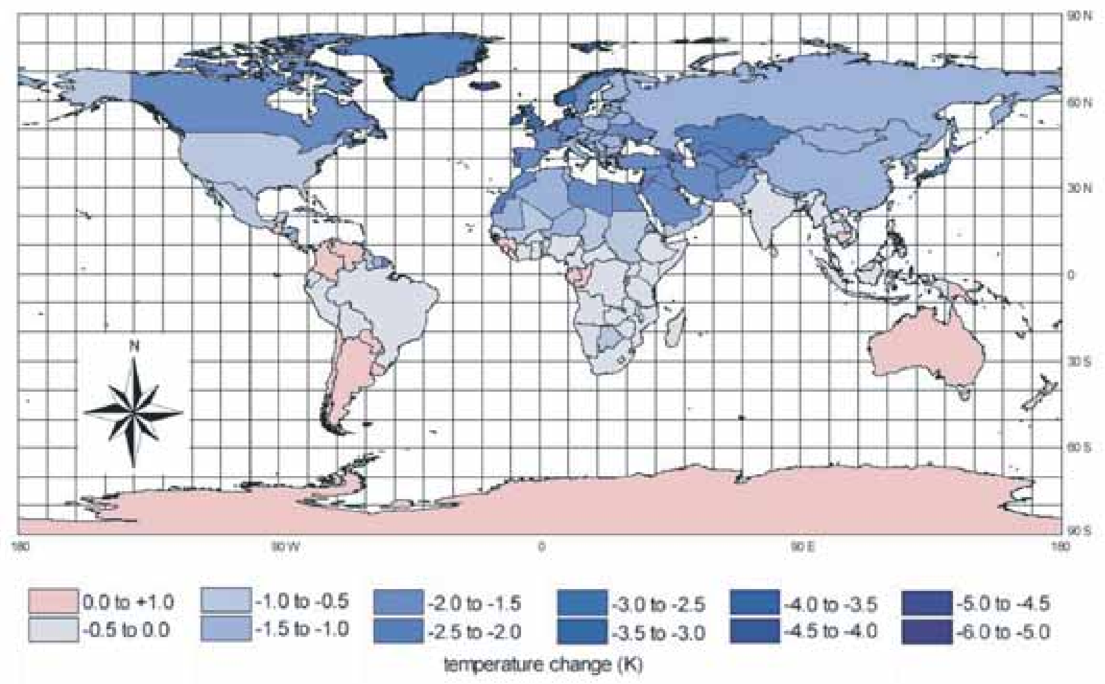

Peter Michael Link

Hamburg 2006

Der Kabeljau

Das Meer ist weit, das Meer ist blau,
im Wasser schwimmt ein Kabeljau.
Da kömmt ein Fischerboot daher,
ich glaub' von links, ich weiß nicht mehr,
fängt ein den Fisch mit Haut und Haar,
das ist zwar traurig, aber wahr. ---
Das Meer ist weit, das Meer ist blau,
im Wasser schwimmt kein Kabeljau.

(verändert, nach Heinz Erhardt)

Acknowledgements

I would like to thank Richard Tol for his supervision of my dissertation and his valuable comments and constructive criticism regarding the various analyses, also for providing the integrated assessment model *FUND*, which was used in the assessments of overall socioeconomic consequences of THC change. I am also grateful to Uwe Schneider for improving my knowledge about optimization modeling and for help in debugging the model code.

Research on the economic impacts of THC change on fisheries was funded by the Bundesministerium für Bildung und Forschung der Bundesrepublik Deutschland as part of the research project INTEGRATION (project no. 01 LD 0016) which was to provide an Integrated Assessment of the consequences of a shutdown of the thermohaline ciruclation. The US National Science Foundation through the Center for Integrated Study of the Human Dimensions of Global Change (SBR-9521914) and the Michael Otto Foundation provided welcome financial support for the global assessments of consequences of THC change.

Many discussions with Svein Sundby, Bjørn Ådlandsvik and Frode Vikebø from the Institute of Marine Research, Bergen, Norway, greatly helped to improve my understanding of fish population dynamics and the Norwegian fisheries. My special thanks also go to the colleagues at the Potsdam Institute for Climate Impact Research, particularly Till Kuhlbrodt and Stefan Rahmstorf, for sharing the insights on the THC and its possible fate.

Thanks to Till Kuhlbrodt for providing the *CLIMBER-2* data, and to Andre Krebber for processing them. The *HadCM3* data of the THC hosing experiment and the control run have been supplied by the Climate Impacts LINK Project (DEFRA Contract EPG 1/1/154) on behalf of the Hadley Centre and U.K. Meteorological Office. Data on fish stock development were provided by Svein Sundby and Harald Gjøsæter from IMR Bergen.

Also, I would like to thank my colleagues at the Research Unit Sustainability and Global Change for help and support during the past years. Special thanks to Christine Röckmann for all the discussions about model setups and simulation results and an outside perspective that helped generate new ideas for the analyses.

Finally, I would like to express my deepest gratitude to my wife Svea. She provided me with constant support and love throughout the years of my work on this thesis, particularly in difficult periods. Her understanding for me spending many weekends at the office struggling with the models and her proofreading of parts of this dissertation with lots of useful comments greatly helped to complete this dissertation.

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Summary

Anthropogenic climate change can trigger a strong decline in strength of the Atlantic thermohaline circulation (THC). Such weakening will have a wide range of impacts, which are not limited to the physical environment of the affected regions, but are likely to affect biodiversity, ecosystem stability, economic activities, water resources, and human energy consumption as well. To improve possibilities for successful adaptation to these altered environmental conditions, it is important to know which regions and societal sectors will be most affected, and how large damages of a THC shutdown turn out to be. This thesis addresses these issues using specifically designed simulation models that are capable of dealing with scenarios of environmental change caused by a weakening of the THC.

In the introductory chapter 1, the concepts of THC weakening, integrated assessment modeling and bioeconomic fisheries modeling are introduced. Furthermore, the bioeconomic simulation model used in this thesis is described in detail.

The first part of the thesis looks at the overall socioeconomic impacts of a reduction in THC strength. An initial assessment of these impacts of a THC shutdown is conducted in chapter 2, using the integrated assessment model *FUND 2.8*. Two cases are compared: one in which the THC weakens by less than a third and later recovers and one in which the THC shuts down almost completely. The results show that the consequences for the North Atlantic region are less pronounced when occurring in the context of global warming than if the THC shutdown had occurred without the background of anthropogenic climate change. The overall and marginal impacts of climate change are negative regardless of the fate of the THC. However, total damages incurred from THC change amount to only a few per cent of GDP in the regions most affected by a THC breakdown, so the overall extent of damages stemming from a THC collapse is fairly limited.

The *FUND* model is improved for the simulations presented in chapter 3 to resolve the socioeconomic impacts of changes in THC strength on a country level. Monetized market and non-market impacts of changes in environmental conditions following a THC collapse are determined for 207 individual countries. Eight different response patterns can be identified. The most frequent pattern observed is one in which a THC shutdown has an offsetting effect on the underlying warming trend. Depending on whether the impacts of warming are initially

beneficial or detrimental, the economic effects of a THC collapse are quite heterogeneously distributed geographically. The analyses indicate that the most important economic sectors affected by an altered THC strength are water resources and energy consumption. Among health related impacts, the changes in the spread of cardiovascular and respiratory diseases are of particular significance. The maximum national impact of a collapse of the THC turns out to be of the magnitude of a few per cent of GDP, whereas the global impact is much smaller. Considering the low probability of occurrence, the scenario of a THC shutdown does not call for drastic action at present.

The second part focuses on the marine fisheries of cod (*Gadus morhua*) and capelin (*Mallotus villosus*) in the Barents Sea region, an important economic sector that is assumed to be particularly affected by changes in the Atlantic THC. In chapter 4, the economic impacts of changes in THC strength on these fisheries are explored using a bioeconomic simulation model. In this assessment, the fishermen follow an adaptive harvesting strategy. A shutdown of the THC is represented by a sudden reduction of the environmental carrying capacities or productivities of the species. The simulations show that in the long run reduced productivity or carrying capacities lead to lower stock sizes and consequently to smaller catches. During the first few years after the change in population dynamics, however, the fisheries are hardly affected. For large changes in productivity or carrying capacity, the cod fishery becomes completely unprofitable. The reduction in economic success is less pronounced for the capelin fishery than for the cod fishery, as the capelin stock can benefit to some extent by a release of predation pressure due to a smaller predator stock size of cod, leaving more capelin to be harvested.

The bioeconomic model is further extended in chapter 5 to allow vessels to enter the fisheries in very profitable periods or to exit if the fishery has become unprofitable. Furthermore, management measures by means of total allowable catches were incorporated. The same scenarios of changes in population dynamics were applied to the improved model version, and simulations were conducted with fisheries using profit-maximizing harvesting strategies. The analyses demonstrate that small changes in population dynamics have only little economic impact. A strong reduction in productivity or carrying capacity, however, has a lasting negative impact on long-term stock development, leading to lower overall catch sizes and consequently to lower income from fishing. Here, the decline in economic activity is particularly significant for the cod fishery not only due to the higher value of the fish but also because of the much larger amount of capital invested in the operation of the fishery. Generally, a lower productivity has a more profound economic impact than a lower carrying capacity.

Simulations with the bioeconomic fisheries model coupled to scenarios of THC change are performed in chapter 6. The model setup is adjusted to incorporate the influence of temperature and THC strength on recruitment success and natural survival rates of the species. Comparisons of landings and returns from fishing in the scenarios with a stable THC and the THC breakdown scenario yield insights about the success of the fleets and their harvesting strategies in case of altered circulation patterns in the North Atlantic Ocean. The simulations demonstrate that a substantial weakening of the THC leads to impaired cod stock development because of lower survival rates of the youngest age classes. This causes 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.

The final chapter 7 summarizes the findings, discusses the relevance of the results and points to areas of socioeconomic impact assessment of THC change that may prove worthwhile subjects of further research.

Zusammenfassung

Eine mögliche Folge des anthropogen verursachten Klimawandels ist eine starke Abschwächung der thermohalinen Zirkulation (THC) im Atlantischen Ozean. Eine derartige Entwicklung hätte vielfältige Folgen. Neben den Umweltbedingungen im Nordatlantischen Raum würde eine geringere Zirkulation auch mittelbar die Artenvielfalt, die Stabilität von Ökosystemen, wirtschaftliche Aktivitäten, die Verfügbarkeit von Trinkwasser sowie den menschlichen Energieverbrauch beeinflussen. Um eine erfolgreiche Anpassung an die veränderten Umweltbedingungen zu ermöglichen, ist es notwendig zu wissen, welche geographischen Regionen und welche Bereiche der Gesellschaft am meisten in Mitleidenschaft gezogen würden und wie groß die Folgeschäden eines Zusammenbruchs der THC letztendlich wären. Diese Doktorarbeit analysiert diese Aspekte mit Hilfe von Simulationsmodellen, die speziell für die Untersuchung von Szenarien eines THC-Zusammenbruchs entwickelt bzw. weiterentwickelt wurden.

Im einleitenden Kapitel 1 erfolgt eine konzeptionelle Einführung die THC und deren mögliche Abschwächung, die Integrated Assessment Modellierung sowie die bioökonomische Modellierung der Fischereiwirtschaft. Außerdem wird das bioökonomische Fischereimodell, welches im zweiten Teil der Dissertation angewandt wird, detailliert beschrieben.

Der erste Teil dieser Doktorarbeit beschäftigt sich mit den gesamtwirtschaftlichen Auswirkungen einer Abschwächung der THC. Eine erste Abschätzung dieser Konsequenzen erfolgt in Kapitel 2 mit Hilfe des Integrated Assessment Modells *FUND 2.8*. Dabei werden zwei Szenarien verglichen: eines, in welchem sich die THC um etwa ein Drittel abschwächt und sich später regeneriert und ein zweites, in welchem die THC fast vollständig zum Erliegen kommt. Die Ergebnisse zeigen, daß die Auswirkungen eines Zusammenbruchs der THC im Nordatlantischen Raum weniger stark ausgeprägt sind, wenn die Zirkulationsänderungen in den Simulationen eine Folge der globalen Erderwärmung sind, anstatt als separates Ereignis bei stabilem Klima betrachtet zu werden. Unabhängig von der Entwicklung der THC sind die Auswirkungen des Klimawandels in beiden Szenarien negativ. Allerdings belaufen sich die wirtschaftlichen Schäden infolge einer THC-Abschwächung lediglich auf wenige Prozent der Bruttowertschöpfung. Dies gilt selbst in den Regionen, die von einem Zusammenbruch der THC noch am stärksten betroffen wären. Dementsprechend

ist das Ausmaß der Gesamtschäden, die aus einem THC-Kollaps resultieren, nach dieser Simulation als begrenzt einzustufen.

Die Analysen in Kapitel 3 basieren auf einer verbesserten Version des *FUND*-Modells, in welcher die sozioökonomischen Auswirkungen einer Verringerung der THC-Stärke für 207 Staaten separat ermittelt werden. Diese Erhöhung der räumlichen Auflösung erlaubt es, acht verschiedene Reaktionsmuster zu identifizieren. In den meisten Ländern führt ein THC-Zusammenbruch zu einer regionalen Abschwächung der Erderwärmung. Die geographische Verteilung der wirtschaftlichen Konsequenzen ist sehr heterogen und abhängig davon, ob ein Land grundsätzlich vom Klimawandel positiv oder negativ betroffen ist. Die Trinkwasserversorgung sowie der menschliche Energieverbrauch sind die beiden Wirtschaftsbereiche, die generell am deutlichsten beeinträchtigt werden. Unter den gesundheitlichen Auswirkungen sind vor allem die Ausbreitung von Herz-Kreislauf- und Atemwegserkrankungen von Bedeutung. Die Gesamtschäden eines Zusammenbruchs der THC belaufen sich auf einige Prozent der Bruttowertschöpfung auf nationaler Ebene, global betrachtet sind die Auswirkungen jedoch äußerst gering. Berücksichtigt man die geringe Eintrittswahrscheinlichkeit eines Zusammenbruchs der Zirkulation, scheinen derzeit keine drastischen Maßnahmen zur Anpassung an deren Folgen notwendig.

Im zweiten Teil der Dissertation wird speziell auf die Hochseefischerei von Kabeljau (*Gadus morhua*) und Lodde (*Mallotus villosus*) in der Barentssee eingegangen, einem bedeutenden Wirtschaftszweig, von dem ausgegangen wird, daß er in besonderem Maße durch Veränderungen in der Zirkulationsstärke betroffen sein wird. Im vierten Kapitel werden mit Hilfe eines bioökonomischen Simulationsmodells die wirtschaftlichen Auswirkungen von populationsdynamischen Änderungen der betrachteten Fischbestände untersucht, wie sie als Folge einer THC-Abschwächung auftreten können. Der Zusammenbruch der THC wird dabei durch eine plötzliche Verringerung der ökologischen Tragfähigkeit oder der Reproduktionsrate dargestellt. In den Analysen in diesem Kapitel folgen die Fischer einer adaptiven Fangstrategie. Die Resultate belegen, daß eine verringerte ökologische Tragfähigkeit oder Reproduktionsrate langfristig zu geringeren Bestandsgrößen und folglich zu kleineren jährlichen Fangmengen führt. Während der ersten Jahre nach den populationsdynamischen Veränderungen sind die wirtschaftlichen Auswirkungen auf die Fischerei jedoch gering. Eine starke Verringerung der Reproduktionsrate oder der ökologischen Tragfähigkeit führt im Endeffekt dazu, daß die Kabeljaufischerei komplett unrentabel wird. Aufgrund der geringeren Zahl an Freßfeinden erhöht sich der Anteil des Loddebestands, der von den Fischern gefangen werden kann. Deshalb sind die wirtschaftlichen Beeinträchtigungen für die Loddefischerei letztendlich deutlich geringer als für die Kabeljaufischerei.

Eine erweiterte Version des bioökonomischen Modells wird in Kapitel 5 verwendet. Die Größen der Fischereiflotten sind nun variabel und können in profitablen Zeiten expandieren bzw. bei geringen Fischereierträgen kleiner werden. Außerdem werden Maßnahmen des Fischereimanagements in Form von maximalen Gesamtfangmengen berücksichtigt. In dieser Analyse, in der die Fischer einer profitmaximierenden Fangstrategie folgen, werden die gleichen Szenarien betrachtet wie im vorigen Kapitel. Die Ergebnisse zeigen, daß geringe populationsdynamische Veränderungen fast keine wirtschaftlichen Nachteile hervorrufen. Eine starke Reduzierung der Reproduktionsrate oder der ökologischen Tragfähigkeit hat jedoch einen dauerhaften schädigenden Einfluß auf die Bestandsentwicklung, was sich auch negativ auf die Fischerei auswirkt. Dabei belastet ein Rückgang in der ökonomischen Aktivität vor allem die Erträge der Kabeljaufischerei, nicht nur aufgrund des höheren Marktwertes des Fisches sondern auch wegen der deutlich höheren Kapitalbindung in der Fischereiflotte. Generell hat ein Rückgang der Reproduktionsrate schwerwiegendere wirtschaftliche Auswirkungen als eine Verringerung der ökologischen Tragfähigkeit.

In Kapitel 6 wird das bioökonomische Modell direkt mit Szenarien der THC-Entwicklung gekoppelt. Die Modellstruktur wurde dahingehend angepaßt, daß der Einfluß der Wassertemperatur auf den Rekrutierungserfolg sowie die Abhängigkeit der natürlichen Überlebensraten von der Stärke der THC berücksichtigt werden. Vergleiche der Fangmengen und Fischereierträge in den Szenarien unterschiedlicher Zirkulationsentwicklung geben Aufschluß über den Erfolg der Fangstrategien der Fischereiflotten in Zeiten sich ändernder THC-Stärke. Die Analysen zeigen, daß eine deutliche Abschwächung der THC die Entwicklung des Kabeljaubestands aufgrund reduzierter Überlebensraten der jüngsten Altersklassen deutlich beeinträchtigt. Dadurch wird die Kabeljaufischerei langfristig unprofitabel. Eine gleichzeitige Verbesserung der Bestandsentwicklung von Lodde hilft zwar der Loddefischerei, diese Veränderung ist jedoch nicht ausreichend, um die größeren Verluste der Kabeljaufischerei auszugleichen.

Das abschließende Kapitel 7 faßt die Untersuchungsergebnisse zusammen und erörtert die Relevanz der Resultate. Schließlich werden weitere Möglichkeiten zur Erforschung der sozioökonomischen Auswirkungen einer Abschwächung der thermohalinen Zirkulation aufgezeigt.

1 Introduction

1.1 Climate change and its consequences

Generally, it is agreed among climate scientists that the Earth’s climate is going to change at an unprecedented rate during the coming centuries (Houghton *et al.*, 2001). The extent of this change, however, is still debated. While the average global surface temperature has risen between 0.4 and 0.8°K over the past century, results from simulations with general circulation models (GCMs) suggest that during the 21st century we will experience an increase in global mean surface temperature between 1.4 and 5.8°K. Such a drastic shift will manifest itself directly in altered precipitation patterns, a reduced ice cover in Polar Regions, and an increase in the frequency of extreme weather events. A modified global climate will also trigger a number of indirect consequences, such as sea-level rise, or changes in ocean circulation patterns, which in turn may lead to shifts in ecosystem composition, or changes in food webs, in both terrestrial and marine habitats. These new conditions require anthropogenic reaction, e.g. adaptation to modified land use patterns, regionally increased energy consumption, shifts in frequency and ranges of diseases, and altered yields of economically exploited renewable resources.

Considering changes in ocean circulation, paleoclimatic records show that there have been rapid climatic shifts in the North Atlantic region during the last glacial cycle and the early Holocene, which can be linked to the strength of the Atlantic thermohaline circulation (THC). These shifts have led to massive ecological changes in European ecosystems (Ammann *et al.*, 2000) in the past. Another strong weakening of the THC in the near future, as suggested by several model analyses (Sarmiento *et al.*, 1998; Emori *et al.*, 1999; Rahmstorf & Ganopolski, 1999; Flato & Boer, 2001), would offset the presumed overall warming trend over Northern and Western Europe to some extent. The most serious consequences of a THC shutdown are expected to affect the North Atlantic marine ecosystems and their economic use, such as marine fisheries (Houghton *et al.*, 2001).

Countries all around the world rely on this economic sector. Total annual catches of marine fish have peaked at a level of approximately 80 million tons in the mid-1980s and have somewhat leveled off since (Watson & Pauly, 2001). The top 20 species contribute almost half of total landings (Houghton *et al.*, 2001), highlighting the significance of the main commercially exploited fish species. The main fisheries in the North Atlantic are those of herring (*Clupea harengus*), capelin (*Mallotus villosus*) and cod (*Gadus morhua*). Statistics of the Fisheries Department of the Food and Agriculture Organization of the United Nations show that half of the worldwide marine fish stocks can be considered to be fully exploited (FAO, 2004). Another quarter is already depleted, overexploited or currently in a state of recovery. Therefore, changes in hydrographic conditions can lead to distinct changes in fish behavior and population dynamics (Wood & McDonald, 1997), including inhibited recovery of stocks under strong stress from commercial exploitation. This poses additional obstacles to the already difficult task of managing fisheries successfully in a world with a changing climate, as fisheries management encompasses distinctly different disciplines such as economics, ecology and sociology (Policansky, 2001).

1.2 The thermohaline circulation

For the understanding of the model scenarios used in the model analyses of this thesis, it is necessary to look more closely at the functionality of the THC. The term thermohaline circulation refers to the combination of variability in water temperature and salinity, causing density differences within the water column, which are an important driving force of ocean circulation. Since water temperature depends on heating or cooling at the ocean surface, and salinity is influenced by freshwater fluxes such as precipitation, inflow from rivers, evaporation, melting, or freezing (Knauss, 1996), the THC is sensitive to changes in climatic conditions.

The THC resembles a large conveyor belt that causes an overturning of the world ocean by formation of deep water in particular geographical regions such as the North Atlantic Ocean and the Antarctic Circumpolar region (Fig. 1-1). These characteristic cold water masses such as the North Atlantic Deep Water (NADW) and Antarctic Bottom water (AABW) spread through the main ocean basins (Knauss, 1996). To compensate for the Southward flow of NADW, warmer near-surface currents flow North in the Atlantic Ocean, transporting approximately 10^{15} W of heat from the tropics into the Nordic Seas by means of the Gulf Stream and the North Atlantic Current (Rahmstorf, 1997). The functionality of this mechanism depends on the pressure gradients in the deep ocean, which allow water to sink. The circulation stops when downwelling is inhibited due to a large stability of the water column. This is the case when the density of surface waters in areas of deep water formation declines too much.

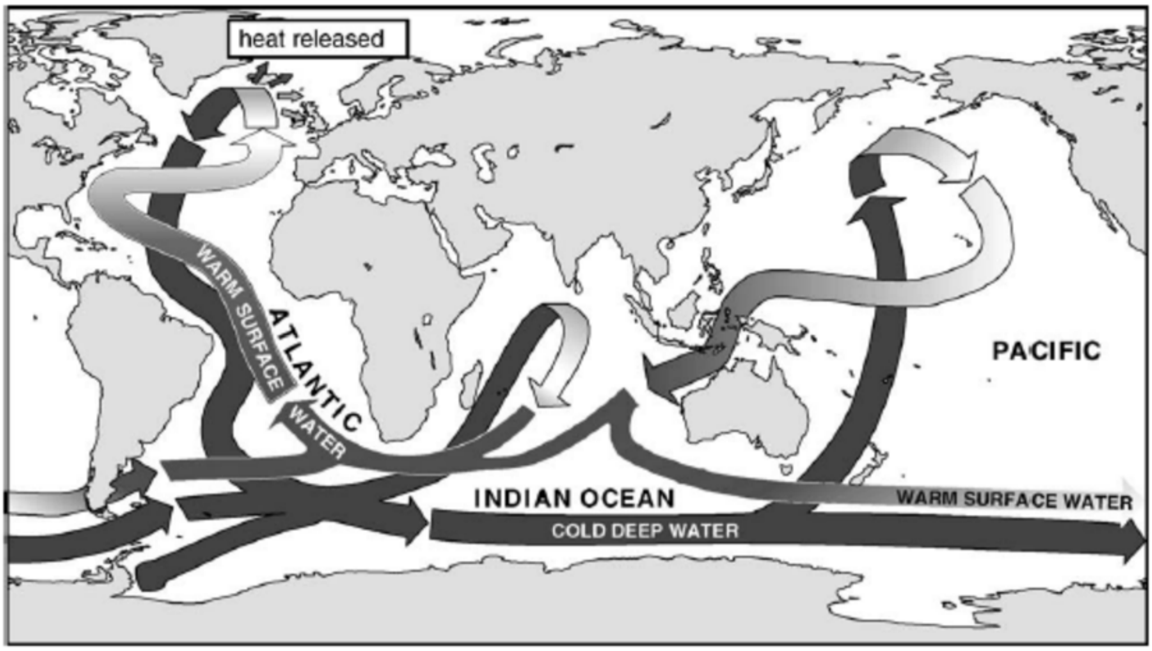

Figure 1-1: Schematic representation of the thermohaline circulation (Hall & Behl, 2006)

Due to the combined influence of temperature and salinity on water density and therefore on the ocean circulation, the behavior of the THC is non-linear (Stommel, 1961). There are two possible equilibrium states of the THC, one with a functioning THC and one in which the THC has collapsed (Rahmstorf, 2000). A freshwater input of approximately 0.15 Sv is sufficient to trigger the transition from the current state to a regime without an Atlantic THC. Most models agree that under current climate conditions the freshwater flux is somewhere below the threshold. Simulation results suggest that in scenarios with severe climate change, enough additional input from melt water, precipitation, or runoff will be added to the North Atlantic to exceed the threshold, causing a regime shift of the ocean circulation (Manabe & Stouffer, 1994).

A collapse of the THC would have a significant effect on climate in the North Atlantic region. Currently, the amount of heat transported from the tropics to the high latitudes causes air temperatures in Northern Europe to exceed the latitudinal mean by about 10°K (Rahmstorf & Ganopolski, 1999). Without a functioning THC, temperatures would drop by up to this amount (Manabe & Stouffer, 1988, 1999). However, while models agree that a THC collapse leads to cooling in the North Atlantic region; there is a discrepancy about the actual magnitude and geographic extent of the cooling: some models place the center of cooling over Northwestern Europe (e.g. Rahmstorf & Ganopolski, 1999), while others show strongest cooling further West, closer to Canada (e.g. Vellinga & Wood, 2002).

The probability of a complete collapse of the THC is actually not too great, since scenarios of extreme climate change are necessary to trigger the breakdown of ocean circulation (Rahmstorf, 1999). More likely is a partial shutdown of the THC with an overall reduction in THC strength by 20 to 50%, a development observed in several model analyses. With a weakening of the THC, climate impacts would be less pronounced but could possibly remain strong enough to still have a considerable influence on both biosphere and anthroposphere in the affected areas.

1.3 Integrated assessment modeling of climate change impacts

Assessments of the overall socioeconomic impacts of climate change utilize so-called integrated assessment models (IAMs). These models are used not only to understand the underlying processes but also to provide information that is useful to decision makers (Schneider, 1997). Furthermore, they tie together many different scientific disciplines, methods, and degrees of data certainty in order to obtain a picture of interactions that remain undiscovered in analyses with a scope of a single discipline. Therefore, they are particularly useful for analyses of the interactions between natural and social systems.

IAMs cannot provide specific advice to decision makers as to how to act in a certain scenario. Due to limitations in computational power, individual processes are usually incorporated in IAMs with less detail than they would in state-of-the-art specialized models (Parson & Fisher-Vanden, 1997). Additionally, the components of IAMs are generally too large and complex, some processes are not yet understood enough to be incorporated, and many quantities considered in IAMs are difficult or impossible to quantify, particularly if monetary values have to be assigned to abstract items such as human life, health, or biodiversity. But IAMs can serve other needs as they are computationally efficient enough to allow for assessments of many possible solutions to a problem based on the variation of assumptions (Barker, 2003). They do provide qualitative insights on how different policies affect climate on a global scale, thus serving as a tool for judging the usefulness of policy options.

In the past, IAMs have mostly considered simple climate change scenarios in order to allow the economic modules to obtain optimal solutions (Hall & Behl, 2006). Real climate instabilities and short-term climate variability have received little attention in IAM modeling. The simplifications incorporated in the climate change modules of IAMs have a considerable influence on the model results and can qualitatively alter the recommended strategies, as complex systems like e.g. the ocean circulation often show non-linear behavior, such as hysteresis or irreversibility (Schneider, 2004). Looking at the factors influencing THC strength, it is not enough too look at the total amount of greenhouse gas emissions. The emission rates play an important role in determining the fate of the THC and therefore the magnitude of expected climate-related damages and should not be dismissed (Stocker & Marchal, 2000; Schneider & Thompson, 2000).

One of the best known IAMs of such complexity is the Dynamic Integrated model of Climate and the Economy (*DICE*) (Nordhaus, 1994), which is an optimal growth model that generates an optimal set of environmental and economic variables for a given set of assumptions. The objective is to maximize discounted utility for given constraints stemming from costs for greenhouse gas emission abatement and damages incurred from changing climate conditions. This model is still used today, generally coupled to additional modules improving the representation of a sector or process that is of particular interest.

In recent years, the possible collapse of the THC has increasingly played a role in IAM analyses. Mastrandrea & Schneider (2001) added a simple ocean circulation module to DICE to include parameterized damages from THC breakdown in the economic assessment. Results showed that carbon taxes turn out to be higher and emission control measures to be more rigorous when possible consequences from THC changes are considered. Thus, in contrast to the optimal solution of the initial DICE model, in which the THC still collapses, the optimal solution of this enhanced version of DICE leads to a preservation of the THC in the long run. Keller *et al*. (2004) go further and perform an assessment of the possibility of THC breakdown using the DICE model. They show that despite large uncertainties involved in the analysis, significant reductions in future CO_2 emissions appear a justified policy, even though climate change damages may turn out to be small in the end.

1.4 The integrated assessment model *FUND*

The two assessments of overall socioeconomic impacts of THC weakening in this thesis utilize the Climate Framework for Uncertainty, Negotiation and Distribution (*FUND*), an integrated assessment model which is developed and first described and applied in Tol (1997). It is actually a combination of fairly simple modules that describe the development of human population, economics, technology, greenhouse gas emissions, atmospheric chemistry, climate, and sea level, as well as their impacts on welfare. The first model versions distinguish nine major regions of the world and calculate impacts of climate change in time steps of one year, covering the time period from 1950 to 2200. Applications initially focus on overall socioeconomic impacts of greenhouse gas emission scenarios and assess the effectiveness of climate policy (e.g. Tol, 1999a; Tol, 1999e). Subsequent additions to *FUND* include an endogenous representation of technological advances (Tol, 2005b), development aid (Tol, 2005a), feedbacks between wealth and human health (Tol, 2002a), and an explicit account of nitrous oxide and methane among greenhouse gases (Tol, 2004a). Together with these advances in model contents, there has been a concurrent improvement in spatial and temporal resolution of *FUND*. The number of world regions differentiated increased from nine to sixteen (Tol, 2002a). The latest version of *FUND* resolves the world on the basis of 207 individual countries (Tol, 2004b). Furthermore, the end of the simulation period was extended from 2200 to 2300 (Guo *et al.*, 2006).

Recent versions of *FUND* were further expanded to assess the socioeconomic consequences in scenarios of changing in THC strength. The first *FUND* analysis using the 16-region model version looks at welfare impacts of the scenarios of THC reduction presented in Rahmstorf & Ganopolski (1999). The second assessment is a more sophisticated analysis of the overall impacts related to THC weakening, which considers all countries separately and builds on the scenarios of a declining THC generated with the *HadCM3* GCM (Vellinga & Wood, 2002).

1.5 The Barents Sea fisheries

Because the most frequently mentioned consequences of a THC shutdown are impacts on the North Atlantic fisheries, agriculture in Northwestern Europe, ocean uptake of CO_2, and impacts related to human health and amenity (Keller *et al.*, 2000), this thesis focuses on the fisheries of Arcto-Norwegian cod and capelin in the Barents Sea. These fisheries were chosen as an emphasis of the analysis since these fish species are of particular economic importance to the countries jointly managing the stocks and because this geographic region is considerably influenced by the large scale changes occurring in the North Atlantic as a consequence of a weaker meridional overturning.

Figure 1-2: Ranges of cod and capelin in the Barents Sea (based on UNEP/GRID-Arendal, 1998)

The Barents Sea (Fig. 1-2) covers an area of approximately 1.4 million km^2 between the Northern coast of Norway, Svalbard, Novaja Zemlja and the Murman coast (Eide & Flaaten, 1994). Under current climate conditions, the Southwestern part of the Barents Sea remains free of ice throughout the year, whereas the Northern and Eastern parts are frozen over during the winter months. The Barents Sea is home to 145 species of zooplankton (Zenkevitch, 1963) and 114 known fish species. The economically most important fish families in the Barents Sea are codfish (12 species) and flounders (11 species). Herring and capelin are the two planktivorous species with the largest commercial importance. Other fish species in the Barents Sea that are commercially exploited are haddock (*Melanogrammus aeglefinus*) and saithe (*Pollachius virens*).

1.5.1 The Arcto-Norwegian cod fishery

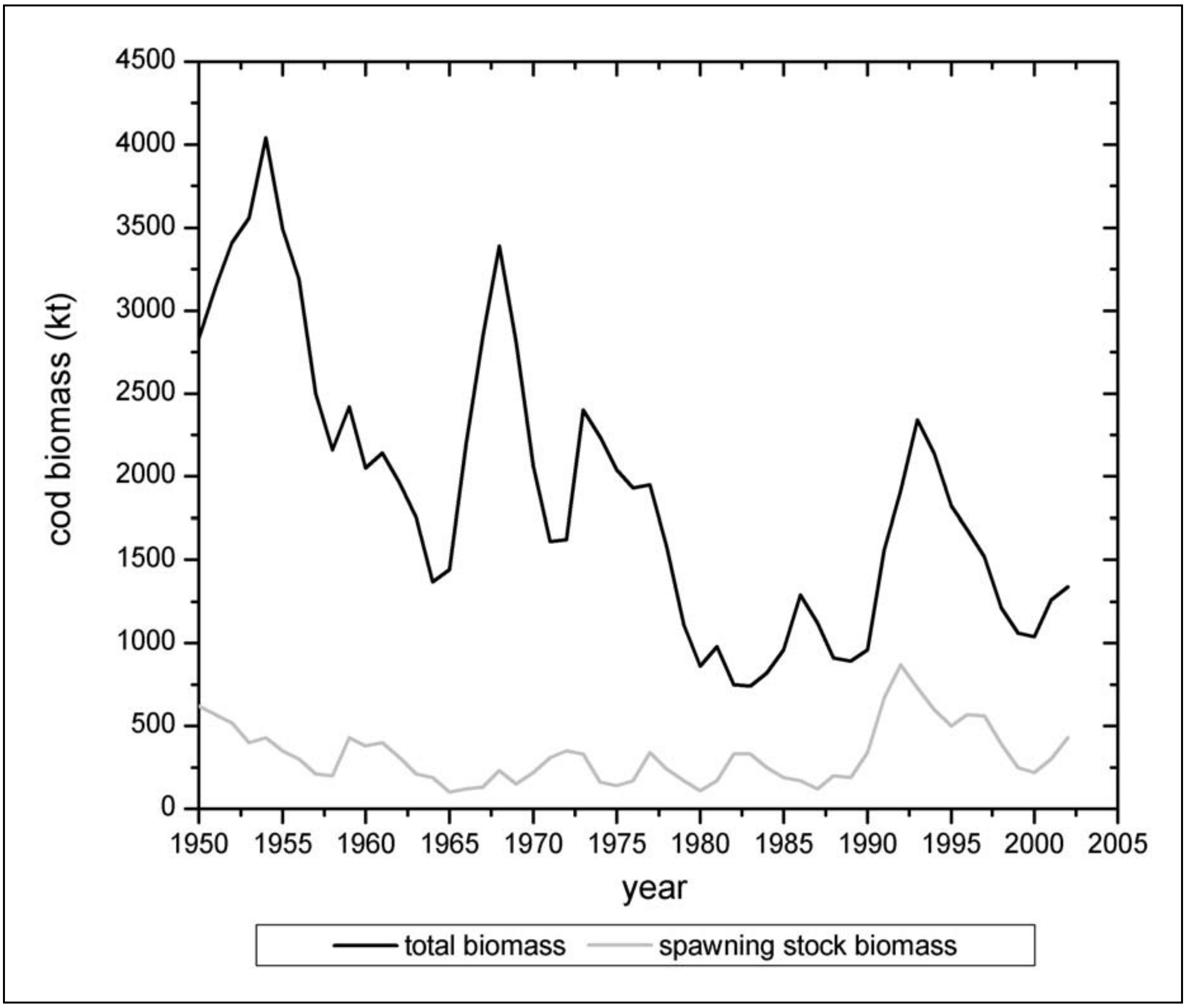

Figure 1-3: Total biomass and spawning stock biomass of Arcto-Norwegian cod (ICES, 2003b)

Arcto-Norwegian cod belongs to the family of *Gadidae* and is one of the most important commercially exploited fish stocks in the world (Sumaila, 1995). Cod preys on herring, capelin, haddock, and on young age classes of its own species (Mehl, 1989). The range of Arcto-Norwegian cod covers most of the Barents Sea, but most cod can be found in the central and Southern regions. In contrast, the cod spawning grounds are geographically confined to the region close to the Lofoten islands off the Norwegian coast, where it spawns in March and April (Fig. 1-2).

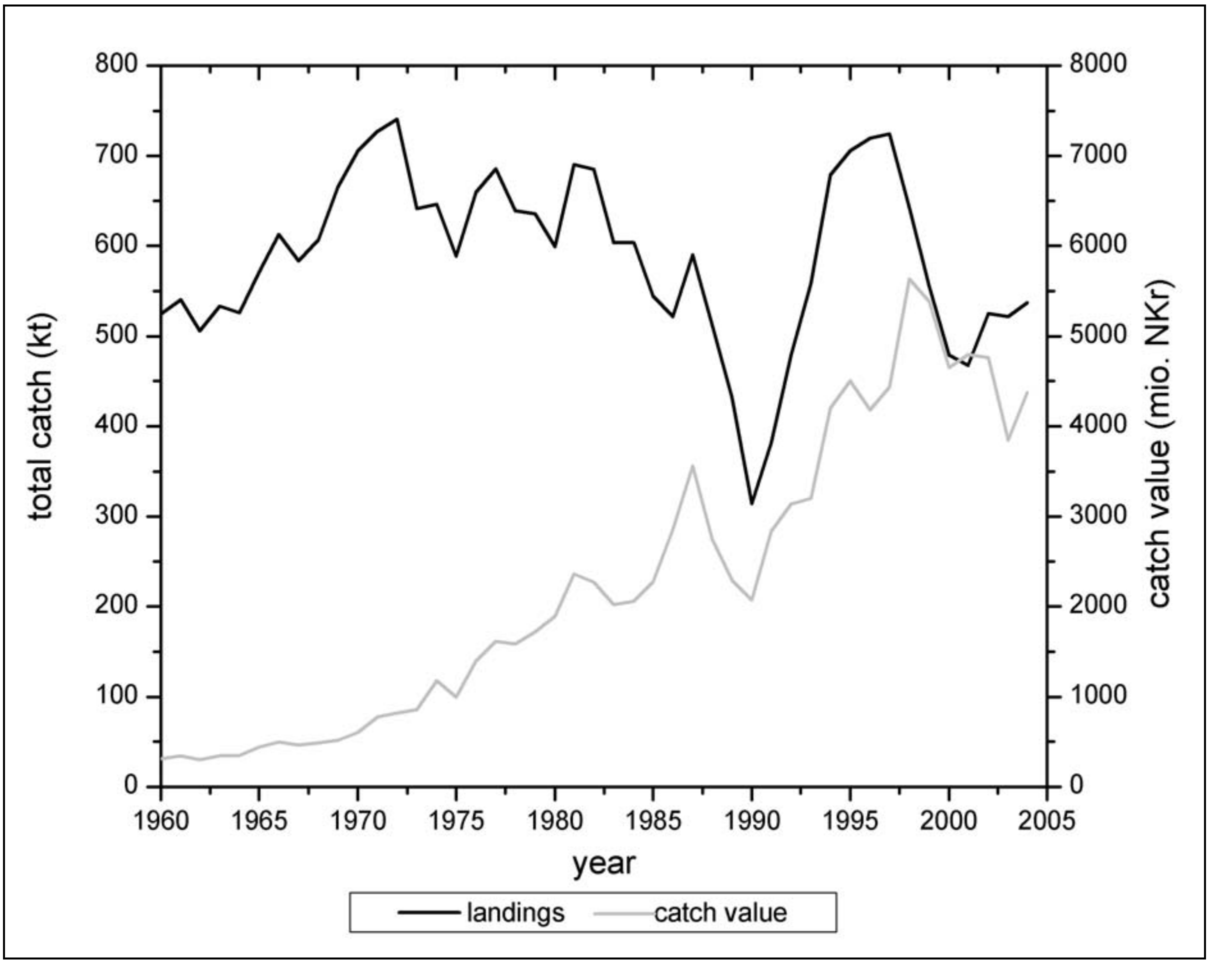

Figure 1-4: Total catch and catch value of codfish (Statistisk Sentralbyrå, 2004)

Estimates of total cod biomass using virtual population analyses conducted by the International Council for the Exploration of the Sea (ICES) allow reconstructions of biomass levels dating back to the 1950s (ICES, 1992). Total stock biomass has been subject to considerable variability in the past, which mainly arises from large differences in recruitment success (Fig. 1-3). Between 1950 and 1980 there was a general downward trend in overall stock biomass due to an expansion of fishing activities, while the spawning stock biomass remained more or less unchanged during this period. Temporary increases in total stock biomass stem from particularly successful recruitment of individual year classes (Mehl & Sunnanå, 1991). Surges in cod stock size usually have direct effects on the stock sizes of prey species. During the 1980s, the main food source of the growing cod stock was capelin and deep-water shrimp (*Pandalus borealis*). Consequently, the capelin stock (Fig. 1-6) decreased in size dramatically in the mid-1980s (ICES, 1987). The situation was similar in the early 1990s, when total cod biomass rose again to more than 2 million tons.

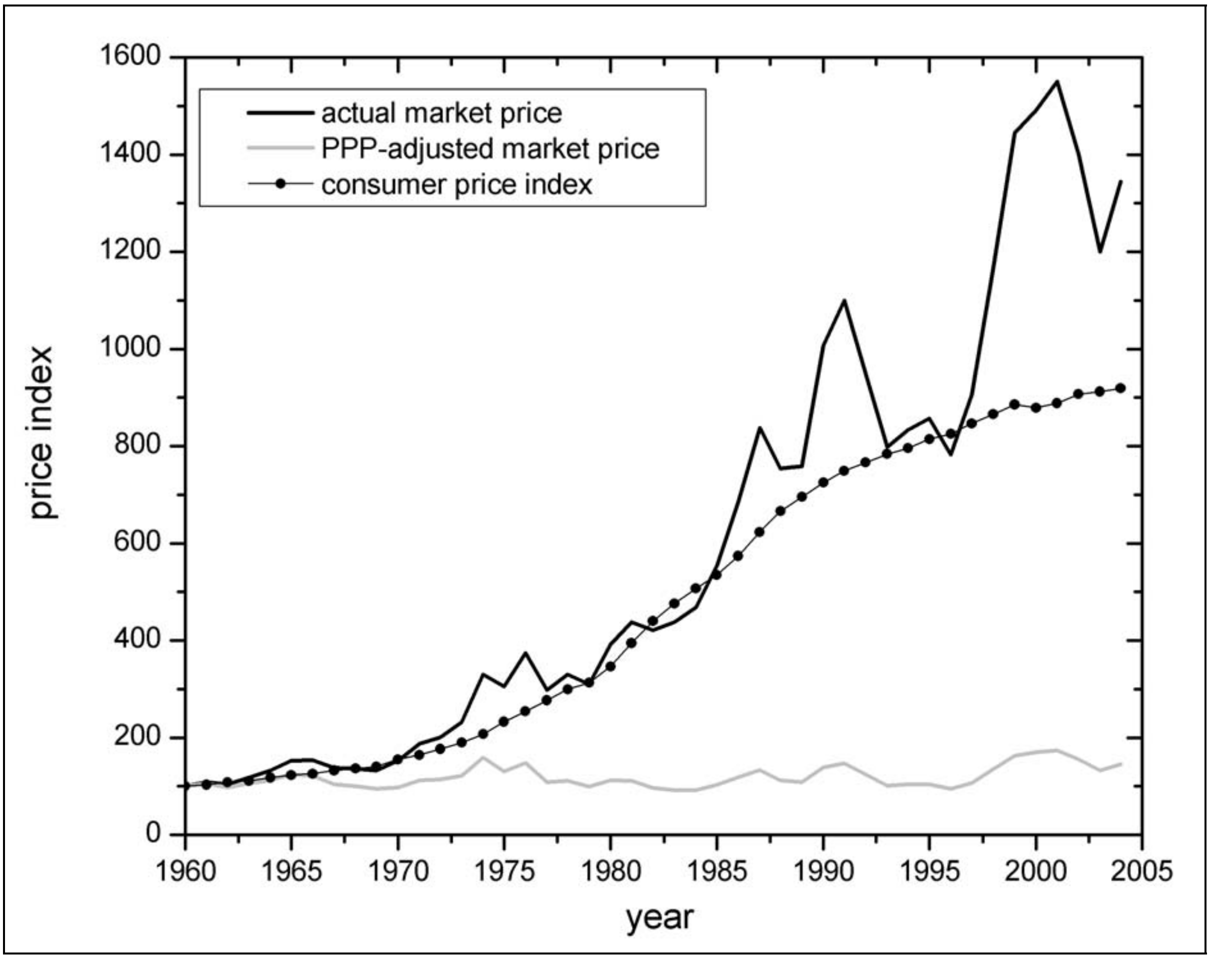

Figure 1-5: Development of the Norwegian market price index of cod with and without adjustment for purchasing power parity and the Norwegian consumer price index (1960 ≡ 100).

Official Norwegian fishery statistics show that catches of codfish increased until the early 1970s before consolidating at high level (Statistisk Sentralbyrå, 2004). In the second half of the 1980s catches of codfish declined sharply (Fig. 1-4). When the cod stock rebounded at the beginning of the 1990s, codfish catches also rose again and temporarily even reached previous high marks. However, landings of codfish have once again declined considerably during the last few years. Currently, approximately 60 Norwegian trawlers and about 600 smaller coastal vessels are engaged in harvesting cod. Cod landings amount to roughly 300.000 tons caught by trawlers and 150.000 tons by coastal vessels, making Arcto-Norwegian cod the single most important species among total Norwegian codfish catches. Despite declining catch levels the value of codfish catches has almost continuously risen in the past, owing to the noticeable increase in market prices. However, it has to be noted that price increases are mainly attributable to inflation, as the market price of cod adjusted for purchasing power parity remains more or less constant regardless of the amount of fish landed (Fig. 1-5).

The exploitation of cod is managed jointly by Norway and Russia. The Joint Norwegian-Russian Fisheries Commission splits TACs and divides the quotas among the countries. In 2004 and 2005, the TAC of Arcto-Norwegian cod was set to 486 000 and 485 000 tons, respectively (Michalsen, 2004; CEC, 2005).

1.5.2 The capelin fishery

Capelin is a small fish that in times of high abundance is one of the dominating species in the Barents Sea ecosystem (Gjøsæter, 1998). Females can reach lengths of approximately 16 cm, male individuals about 19 cm. In contrast to cod, the life expectancy of capelin is limited to roughly 5 years. Adult capelin spawn between age 2 and 5. Generally, capelin die after spawning.

The geographic range covered by capelin varies annually and depends on the hydrographic conditions in the Barents Sea (Ozhigin & Luka, 1985). In years with water temperatures exceeding the long-term average, capelin reaches far North and Northeast regions of the Barents Sea, whereas the range is much smaller and shifted towards the Southern and Western regions of the Barents Sea in the colder years. Spawning takes place mainly in March and April along the Northern coast of Norway and the Kola Peninsula (Fig. 1-2).

Since 1971 the stock size and range of capelin are measured by acoustic means. Gjøsæter (1998) analyzes these measurements and shows that capelin was mainly found in the Northern part of the Barents Sea between 1972 and 1976. During the following years, the main population of the capelin stock moved to the Southwest. Today, the stock covers most of the Barents Sea. The degree of overlap between capelin and its predators significantly influences the extent of predation losses of the total stock. The strong decline of capelin and the concurrent recovery of the cod stock in the 1990s suggest that both species covered a similar range during this time period, whereas there has been only little overlap in the 1970s, which led to much lower predation losses of capelin.

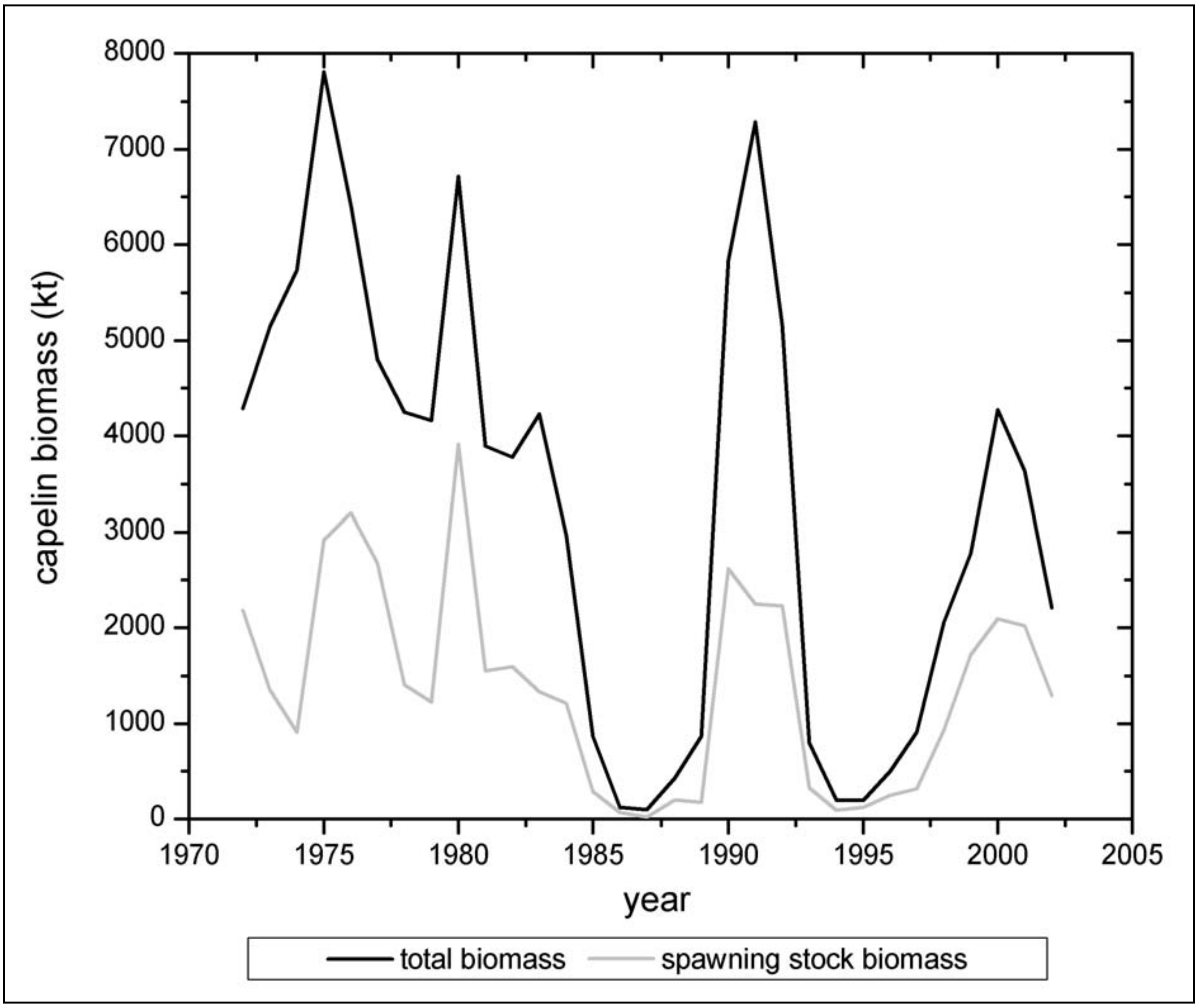

Figure 1-6: Total biomass and spawning stock biomass of capelin (Gjøsæter *et al.*, 1998; IMR Bergen, 2003, pers. comm.)

Between 1972 and 1984 the capelin stock size was fairly stable (Fig. 1-6). On average, the stock consisted of roughly 400 billion individuals or approximately 4 million tons of biomass (Gjøsæter *et al.*, 1998). The strong short-term variability such as the rise in stock biomass in 1980 can be attributed to the particular recruitment success of a limited number of year classes. During the collapse of the stock in the mid-1980s and 1990s, total stock biomass declined within a very short period of time to 0.3 million tons. However, it recovered as quickly as it fell.

Annual landings of Barents Sea capelin exceeded one million tons during the stable period of capelin stock size until the mid-1980s (Fig. 1-7). Then the stock collapsed over a very short period of time, which forced a closure of the fishery until 1990 (Gjøsæter *et al.*, 2002). During stock recovery, the fishery was re-opened but catches were fairly low. Fishing activities ceased again from 1994 until 1998. The following rise in stock size was rather short-lived so that harvesting of Barents Sea capelin could only occur for a few years. As a consequence of the most recent stock decline, the fishery was closed once more. This closure was based on the harvesting strategy of capelin, which sets the total allowable catch (TAC) such that the probability of the spawning stock biomass remaining above a threshold of 200,000 tons is 95% (CEC, 2005). Because of the substantial variability in capelin stock size, the capelin TAC based on this strategy is zero quite often.

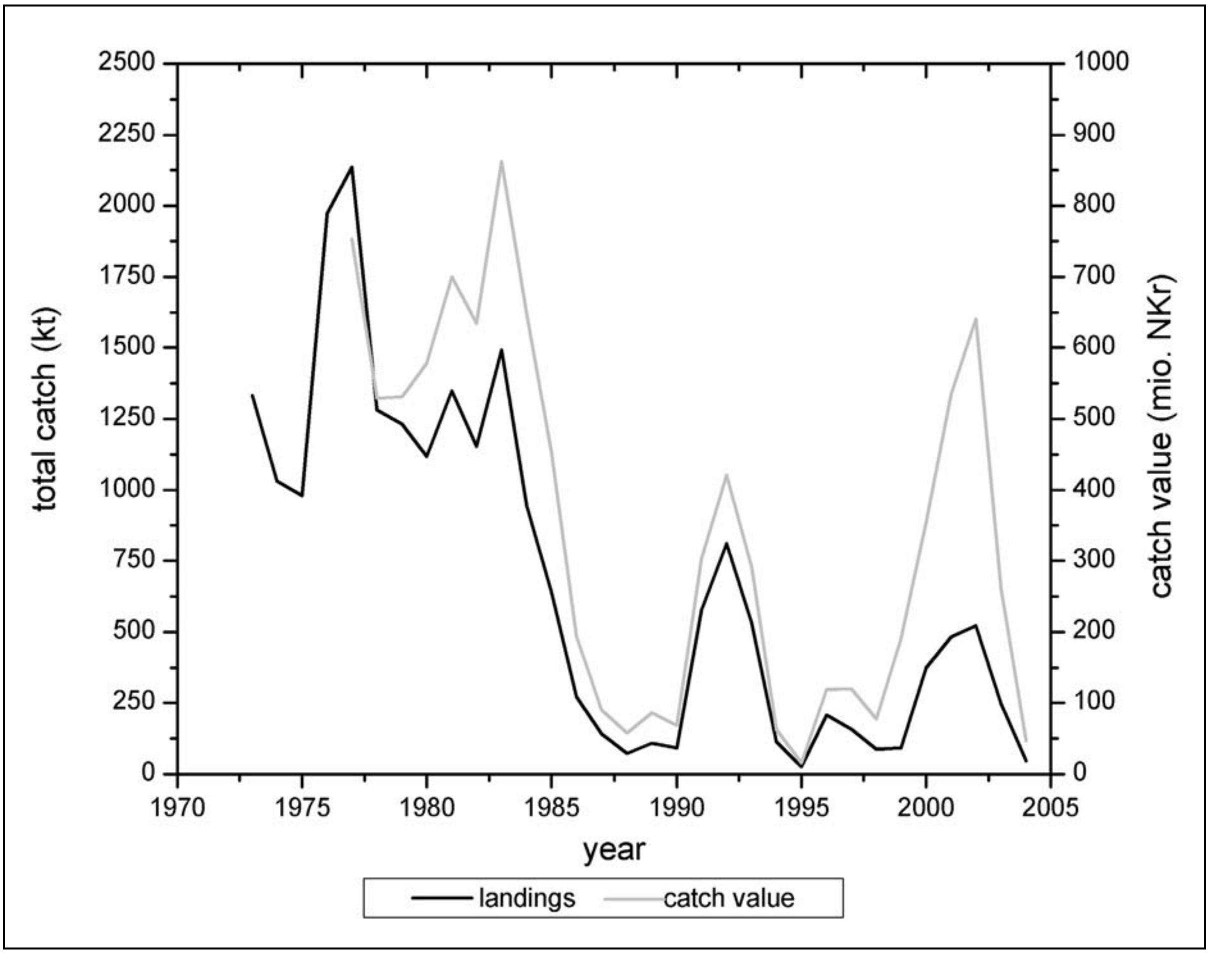

Figure 1-7: Total catch and catch value of capelin (Statistisk Sentralbyrå, 2004)

1.6 Modeling of the Barents Sea fisheries

In order to optimally utilize the renewable resources in the Barents Sea, bioeconomic models of the fisheries have been developed, which allow analyses of the biological and economic consequences of different management strategies or different economic regimes.

Initially, models of Barents Sea fish stock assessment focused on a single species and considered only biological processes. The model *CAPELIN* was a first attempt to simulate the development of the capelin stock size (Tjelmeland, 1985), which was used to determine the harvest amount that would lead to an optimal further development of the stock. Another model used to assess the short-term development of the capelin stock is the model BIFROST (Gjøsæter *et al*., 2002). However, the focus on a single fish species has the disadvantage that species interactions are neglected which might reduce the predictive value of the results obtained.

Multispecies models address this issue; however, complete versions of multispecies models are usually too complex and computationally inefficient for systematic use in fisheries management. Aggregated versions of the multispecies models *ECONMULT* (Eide & Flaaten, 1993) and *MULTSPEC* (Bogstad *et al*., 1997) have been developed to be used for management purposes: the models *ECONSIMP* and *MULTSIMP* (Eide & Flaaten, 1994). Analyses with these model versions show that it is economically advantageous to catch both cod and capelin, instead of just harvesting the more valuable cod and leaving the capelin in the sea as additional food source for cod. Moxnes (1992) includes uncertainty in his model of the cod and capelin fisheries in the Barents Sea. He shows that the consideration of uncertainty arising from e.g. random variations, measurement errors or uncertain parameters can have a pronounced impact on the model results and thus also on management decisions.

Sumaila (1995) developed a bioeconomic model of the cod fishery in the Barents Sea that considers different fleet types. He uses the model to determine the size of the fishing fleets that is necessary to optimally exploit the cod stock in the Barents Sea. This model was expanded to include the predator-prey-relationship between cod and capelin (Sumaila, 1997). Economically optimal results are determined for various economic regimes. It is shown that a joint strategy of harvesting both fish stocks leads to substantially higher profits from fishing than an uncoordinated and competitive exploitation of these marine resources, a result comparable to Moxnes (1992).

Eide (1997) and Armstrong & Sumaila (2000) analyze the influence of cannibalism within the cod population on the fisheries of cod. Results show that economically optimal use of the cod stock can only be achieved if the impact of cannibalism is not neglected (Eide, 1997). A shift of fishing effort in the cod fishery from trawlers towards the smaller coastal vessels would lead to an improvement of the economic results in the long run (Armstrong and Sumaila, 2000), as the latter generally target older age classes of the cod population than the former, leaving more younger individuals in the stock to improve the age structure and the overall state of the standing stock, while minimizing cannibalism within the stock.

Armstrong & Sumaila (2001) assess the distribution of the TAC of cod among the trawlers and coastal vessels and the implications of a possible introduction of individual transferable quotas (ITQ) for the Barents Sea fisheries. They show that an introduction of ITQs would not result in a significant improvement of the economic output due to possible negative effects arising from one fleet type buying up all quotas.

All the studies mentioned above analyze specific aspects of the Barents Sea fisheries. However, environmental change is not addressed specifically in these models. Indeed, this is seldom addressed (Knowler, 2002). The assessments of impacts of climate change on the capelin and cod stocks conducted so far focus mainly on biological consequences.

E.g., Malmberg & Blindheim (1994) analyze the influence of environmental conditions on the development of the capelin stock in Icelandic waters. Abundance and growth of capelin vary directly with salinity and indirectly with temperature as zooplankton, which is the prime food source of capelin, is less abundant in cold years and its availability is critical for the development of the capelin stock (Jakobsson, 1992). Carscadden *et al.* (2001) assess the influence of changes in the environment, predation, food availability, and commercial exploitation on capelin population dynamics in the Northwest Atlantic. They show that colder water temperatures lead to Southward shifts in species range, particularly during the cold period observed in the 1990s. An analysis of capelin distribution with respect to climate conditions in the North Atlantic shows that capelin reacts quickly to environmental change (Rose, 2005). It is expected that global warming of 2-4°K during the 21st century leads to a

Northward shift of the capelin range by several hundred kilometers, as the species has shown a similar behavior in the past (Tåning, 1948). Furthermore, fish growth is reduced and spawning takes place later (Carscadden *et al.*, 1997) if climate conditions for capelin deteriorate.

The influence of environmental conditions on cod population dynamics is somewhat different. Sætersdal & Loeng (1987) show that strong year classes of cod recruitment have historically occurred mainly in warm periods or shortly before shifts towards a warmer regime. Ellertsen *et al*. (1989) explain this temperature-recruitment relationship with the temperature-dependent abundance of zooplankton near the spawning grounds of Arcto Norwegian cod, which is critical for the survival of cod larvae. The dependence of successful cod recruitment on favorable climate conditions is stronger in situations of stock depletion (Brander, 2005). An analysis of historic stock development of Atlantic cod off the Newfoundland coast shows that major fluctuations in stock size can be attributed mainly to temperature effects until the middle of the 20th century (Rose, 2004). From then on, stock collapses were as much a consequence of high fishing pressure, creating an additional obstacle for successful stock recovery.

In order to obtain insights on the socioeconomic implications of such changes, Lorentzen & Hannesson (2005) explore the impacts of global warming on the Norwegian fisheries of Arcto-Norwegian cod. An assumed increase of approximately 1.5°K of the Barents Sea could increase annual cod landings by roughly 100 000 tons. Additional profits, however, may diminish as a consequence of market prices falling with a higher cod supply. Furthermore, shifts in migration patterns and species range as a consequence of warming are likely to affect the influence on management decisions of Russia and Norway, the two countries jointly exploiting the Arcto-Norwegian cod stock (Hannesson, 2004).

All in all, while the biological implications of changes in environmental conditions on the major fish stocks in the Nordic Seas have been already assessed to some extent, there is still a lot to be learned about how this translates into economic consequences for the fisheries exploiting these renewable resources, as no analyses have been conducted so far that link economic models with a focus on the North Atlantic fisheries to concrete scenarios of climate change.

1.7 The bioeconomic simulation model of the Barents Sea fisheries used in this thesis

symbol	meaning
a	index denoting the age class
A	highest age class of a species
B	biomass
cap	index referring to capelin
cod	index referring to cod
D	prey density
e	fleet utilization
g	rate of reproduction
G	expected growth of the stock
h	harvest
harv	index denoting the stock size after harvesting has been considered
hum	index referring to human consumption
i	index denoting the fleet type
ind	index referring to industrial use
init	index referring to the beginning of a fishing period
K	carrying capacity
n	number of individuals in an age class
P	fish price
pred	index denoting the stock size after harvesting and predation have been considered
q	catchability coefficient
r	revenue
R	recruitment
s	index denoting the species
SSB	spawning stock biomass
sw	spawning weight
t	index denoting the fishing period
v	number of vessels
w	weight
α	parameter used in recruitment function
β	parameter used in recruitment function
δ	discount factor
ε	environmental variability term used in recruitment function
E	natural variability of temperature in cod and capelin spawning grounds
ζ	parameter used in function relating recruitment to spawning temperatures
η	random variable
θ	variable costs
Θ	cost per unit effort
$\kappa1$	rate of predation
$\kappa2$	parameter used in calculation of predated biomass
λ	learning factor
μ	share of mature individuals
π	profit per fishing period
Π	net present value of profits over the period of interest
ρ	parameter used in function relating recruitment to spawning temperatures
σ	parameter used in function relating recruitment to spawning temperatures
ς	parameter used in function relating recruitment to spawning temperatures
τ	parameter used in function relating recruitment to spawning temperatures
φ	fixed costs
χ	natural survival rate
ψ	total costs

Table 1-1: List of symbols used in the bioeconomic fisheries model

As global warming and a possible weakening of the THC affect the Barents Sea region in the long run, a regular bioeconomic model is insufficient for analyses of the economic impacts of such environmental change. For this kind of assessment it was therefore necessary to develop a long-term bioeconomic model that retains the features of short-term economic analysis while covering a much longer simulation period than conventional bioeconomic models.

The bioeconomic simulation model used in this thesis covers a time period of 100 years, representing the 21st century. It considers two fish species, cod and capelin. It addresses trawlers and coastal vessels that harvest cod, and purse seine vessels that are used to catch capelin. The duration of a fishing period is one year, which is the temporal resolution of the model.

During each fishing period, both fish stocks are subject to several processes for which the calculations are performed sequentially. First of all, harvesting activities must be considered. Catches are calculated and the number of fish in the particular age classes is reduced accordingly. Afterwards, the extent of predation is determined. The stock size of the prey species is reduced while the predators’ weight increases depending on the amount of prey consumed. Then the size of the spawning stock and the number of recruits are calculated for each species. Finally, the stock composition at the beginning of the next fishing period is determined by applying natural mortality and ageing, and then adding the recruits to the stocks. A summary of all symbols used in the model is given in Table 1-1.

1.7.1 Population dynamics of cod

In its natural environment, cod can reach a high age. In the model 15 age classes a are distinguished for cod. Such a setup has already been used by Moxnes (1992) and Sumaila (1995).

At the beginning of a fishing period, the number of individuals in each age class $n_{cod,a,t}^{init}$ is known. Using the average weight of an individual in each age class $w_{cod,a,t}$ the initial stock biomass can be determined.

(1-1) $$B_{cod,t}^{init} = \sum_a w_{cod,a,t} n_{cod,a,t}^{init}$$

The number of individuals in the stock is reduced by the amount harvested by the fishing fleets.

(1-2) $$n_{cod,a,t}^{harv} = n_{cod,a,t}^{init} - \sum_i h_{cod,i,a,t}$$

The recruitment of young cod into the lowest age class depends on the size of the cod stock at the end of a fishing period. The spawning stock biomass $SSB_{cod,t}$ is a function of the number of individuals in each age class $n_{cod,a,t}^{harv}$, the share of mature individuals in each age class $\mu_{cod,a}$ and the spawning weight $sw_{cod,a}$. The recruitment $R_{cod,t}$ depends on the spawning stock biomass and is calculated using the Beverton-Holt recruitment function (Beverton & Holt, 1954).

(1-3) $$SSB_{cod,t} = \sum_a \mu_{cod,a} sw_{cod,a} n_{cod,a,t}^{harv}$$

(1-4) $$R_{cod,t} = \frac{\alpha_{cod,t} SSB_{cod,t}}{1 + \beta_{cod,t} SSB_{cod,t}}$$

where the spawning stock biomass is in units of 1000 tons and recruitment is in millions of fish. The parameters α and β used in the recruitment function depend on the reproductive potential and the environmental carrying capacity of the fish species and are determined by a procedure described in Clark (1990). The values of these parameters may change over time depending on the environmental conditions and are therefore adjusted in the model at the beginning each fishing period.

When the climate change scenarios are applied, the altered environmental conditions mainly manifest themselves through variation in recruitment success and survival rates. Besides depending on spawning stock biomass, cod recruitment is also influenced by the water temperature in the spawning grounds at time of spawning (Ellertsen *et al.*, 1989). Recruitment is always low in cold years whereas in warm years recruitment can be but does not have to be high, as recruitment variability also increases with temperature. This leads to a recruitment function that is both dependent on *T* and on *SSB*.

$$R_{s,t} = f\left(T_t, SSB_{s,t}\right) = \left(\rho_s T_t + \sigma_s\right)\varepsilon_{s,t}\left(SSB_{s,t}\right) \tag{1-5}$$

The first term refers to the maximum possible recruitment at a given temperature and ε denotes a recruitment variability term between 0 and 1, which depends on the spawning stock biomass to find the actual recruitment. It can be determined by relating the quotient of actually observed recruitment and maximum possible recruitment at a given temperature to the spawning stock biomass in that spawning season (Fig. 1-8).

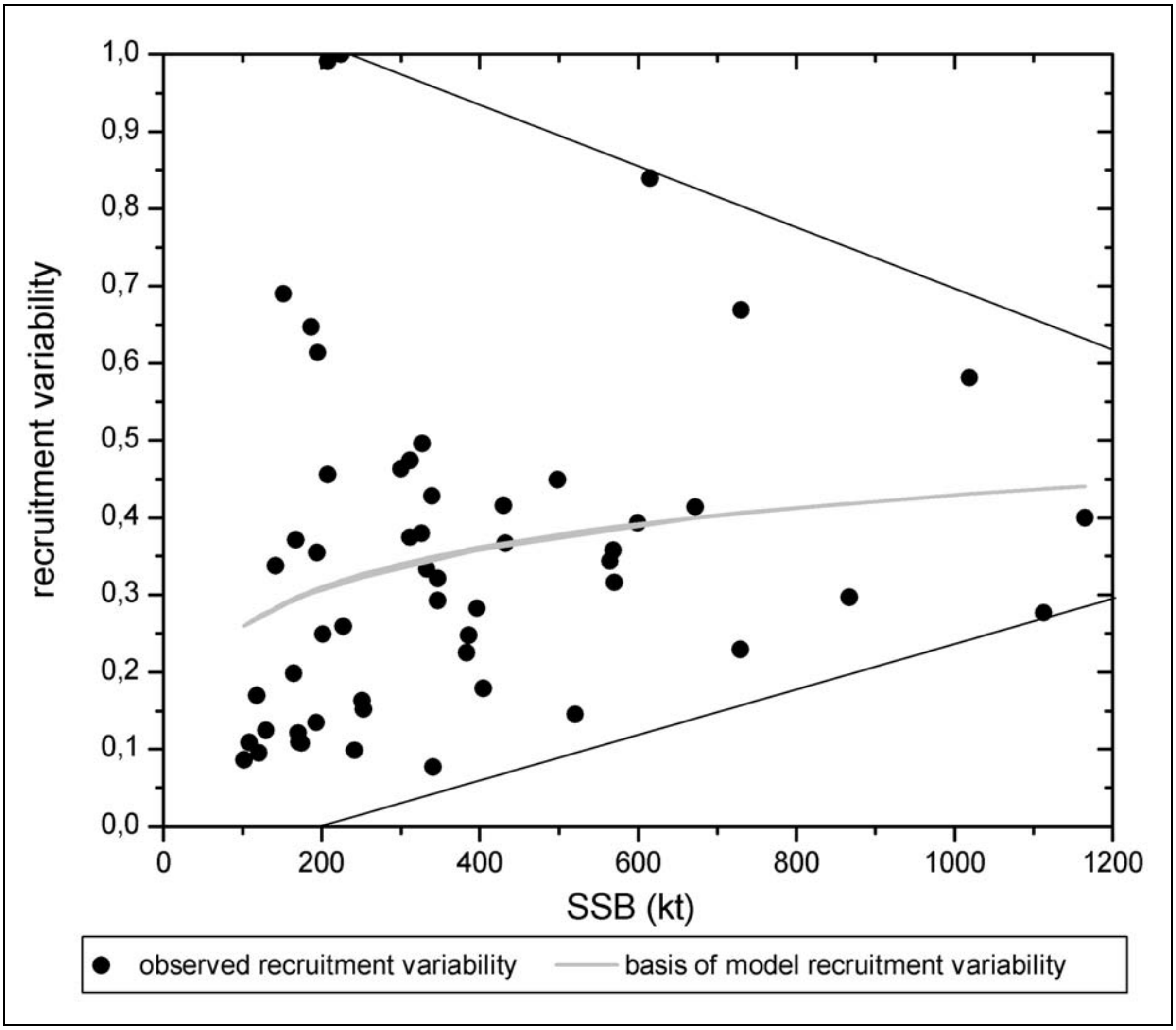

Figure 1-8: Recruitment variability as a function of spawning stock biomass.

Taking into account the diminishing fluctuations of ε with increasing *SSB*, the functional form of recruitment variability becomes

(1-6) $$\varepsilon_{s,t}\left(SSB_{s,t}\right)=\left(\varsigma_s \ln\left(SSB_{s,t}\right)-\tau_s\right)+\left(1-\xi_s SSB_{s,t}\right)\eta$$

where the first term determines the basis of the model recruitment variability for the given *SSB* and the second one determines the actual value within the allowed variability range.

A certain share χ of the individuals of each age class at the end of a fishing period survives until the beginning of the next fishing period to make up the next higher age class then. The highest age class *A* consists of all individuals that have reached or passed that age since it is assumed that cod that is older than 14 years does not grow anymore. New codlings are recruited into the age group 1. Stock sizes with the index *init* refer to the beginning of a fishing period, while the index *harv* refers to the end of a fishing period.

(1-7) $$\begin{aligned} n^{init}_{cod,1,t+1} &= R_{cod,t} \\ n^{init}_{cod,a+1,t+1} &= \chi_{cod,a} n^{harv}_{cod,a,t} \\ n^{init}_{cod,A,t+1} &= \chi_{cod,A} n^{harv}_{cod,A,t} + \chi_{cod,A-1} n^{harv}_{cod,A-1,t} \end{aligned}$$

When the bioeconomic model is linked to the climate change scenarios, the survival rate of cod is made independent of THC strength only for age classes 3 and older, since survival of cod larvae decreases with declining THC strength (Vikebø *et al*., 2005), For the youngest two age classes of cod, the survival rate becomes

(1-8) $$\chi_{s,a,t}=0.81-0.08\left(THC_{ref}-THC_t\right)$$

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

Growth of cod strongly depends on the amount of capelin in the diet of cod, since capelin is one of the most important food sources of cod (Magnússon & Pálsson, 1991). In the model the increase in weight of cod from one age class to the next is a function of the amount of capelin that cod consumed during that respective period of time.

(1-9) $$w_{cod,a+1,t+1} = w_{cod,a,t} + \widehat{w}_{cod,a}\left(D_{cap,t}\kappa_2 + \left(1-\kappa_2\right)\right)$$

The higher the predation of cod on capelin, the larger the weight increase of cod. This way, the effect of the predator-prey-relationship on the cod stock can be captured in the model even though the number of individuals in the cod stock is not affected. It is assumed that only age 2 and older cod prey on capelin (Bogstad & Gjøsæter, 2001).

1.7.2 Population dynamics of capelin

In the model, five age classes are distinguished for capelin. The numbers of individuals are calculated the same way as for the cod stock with the only exception that capelin recruitment is in units of billions of individuals for scaling reasons. Also, the number of capelin left in the stock after harvesting is considered is reduced further due to predation by cod. The extent of predation depends on the prey density at the end of each fishing period. If the cod biomass is high relative to the capelin biomass, the proportion of capelin eaten by cod is also high.

The number of individuals in each age class that is consumed by cod is calculated based on a scheme by Moxnes (1992) that was adapted in such a way that the number of capelin consumed by cod can never be greater than the number of individuals left in the stock. The biomass of capelin that is consumed by cod $B_{cap,t}^{pred}$ is dependent on the size of the cod population $B_{cod,t}^{harv}$, the relative abundance of the prey $D_{cap,t}$, and the rate at which cod preys on capelin κ_1:

(1-10) $$B_{cap,t}^{pred} = \kappa_1 D_{cap,t} B_{cod,t}^{harv}$$

$D_{cap,t}$ is a function of the capelin stock biomass at the end of the fishing period $B_{cap,t}^{harv}$:

(1-11) $$D_{cap,t} = \frac{D_{cap}^{\max}}{1+\left(D_{cap}^{\max}-1\right)\left(\dfrac{B_{cap,t}^{harv}}{B_{cap}^{std}}\right)^{-\gamma}}$$

$D_{cap,t}$ approaches a maximum value of D_{cap}^{max} when the stock biomass increases, since predation by cod cannot increase indefinitely even when the prey is very abundant. The quantity B_{cap}^{std} denotes the size of the capelin stock at which $D_{cap,t}$ takes on a value of 1. This resembles the type 2 functional relationship between the number of prey consumed and the total number of prey as described in Holling (1965). Based on $B_{cap,t}^{pred}$ the number of individuals of capelin that are consumed by cod is determined and the capelin stock is reduced accordingly.

Now it is possible to calculate the capelin stock size at the beginning of the next fishing period, considering the natural survival rate of capelin and the recruitment of a new age class. This is done in the same manner as for the cod stock using the Beverton-Holt recruitment function or the temperature-SSB-recruitment relationship described above, depending on the context. However, capelin recruitment is also critically dependent on the presence of young herring in the Barents Sea (Gjøsæter & Bogstad 1998). In the simulations using the *CLIMBER-3α* scenarios, capelin recruitment is reduced by 90% if herring are present. It is assumed that the likelihood of herring being present in a given year increases stepwise with temperature from practically zero if the spring Barents Sea temperature is below 2.5°C to 50% for temperatures above 7.5°C.

In contrast to cod, the average weight of an individual capelin of a certain age remains constant over time. Therefore, the weights-at-age do not have to be recalculated each fishing period.

Similar to the cod stock, a certain share of each age class of the capelin stock dies due to natural reasons. This has to be considered when updating the age classes. However, in capelin there is no accumulation of individuals in the oldest age class since the capelin older than 5 years rarely occur (Gjøsæter, 1998).

(1-12)
$$n_{cap,1,t+1}^{init} = R_{cap,t}$$
$$n_{cap,a+1,t+1}^{init} = \chi_a n_{cap,a,t}^{pred}$$

1.7.3 The fisheries

For each fishing period and vessel type, the number of fish of each species and age class harvested $h_{s,i,a,t}$ is calculated. The indices used denote the species (s), the fleet (i), the age class (a) and the fishing period (t). The catch size depends on the catchability coefficient $q_{s,i,a}$, the number of fish in each age class $n_{s,a,t}^{init}$ at the beginning of the fishing period and on the fishing effort. The fishing effort is a function of the number of vessels $v_{s,i}$ and their utilization $e_{s,i,t}$.

$$(1\text{-}13) \qquad h_{s,i,a,t} = q_{s,i,a} n_{s,a,t}^{init} v_{s,i} e_{s,i,t}$$

The catchability coefficients are defined in such a way that the fact is considered that each fishing fleet catches only fish of certain age classes. Therefore, the fishing activity of each fleet has a characteristic effect on the fish stock. In the model it is assumed that the fishery of capelin harvests only individuals of age 3 or older. This is done because the fishery at present harvests almost exclusively mature fish, and very few fish younger than 3 years are mature (Gjøsæter, 1998). Trawlers only catch cod of age 4 or older, the coastal vessels only harvest cod that is at least 7 years of age.

Based on the number of fish caught, the weight of the entire catch of both species is determined for each fishing period. It is assumed that all fish is caught prior to spawning so that the fish harvested cannot contribute to reproductive success in any way. This makes it possible to calculate sequentially the reduction of the stocks by harvesting, predation, and the increase of the stock size due to reproduction, before the stock sizes at the beginning of the subsequent fishing period are determined.

The revenues from fishing r of each fleet depend on the market price of the fish P and the size of the entire catch in the respective fishing period. It is assumed that the market price of fish remains constant.

$$(1\text{-}14) \qquad r_{i,t} = \sum_{s,a} P_{s,i} h_{s,i,a,t} w_{s,a,t}$$

The total costs of fishing per vessel ψ consist of fixed costs φ for the support of the fleet that are independent of the extent of use of the fleet and of variable costs θ that depend on the fishing effort exerted.

(1-15) $$\psi_{i,t} = \varphi_i + e_{i,t}\theta_i$$

The profit of each fleet per fishing season π is the difference between total revenues from fishing and the total costs of operating the fleet.

(1-16) $$\pi_{i,t} = r_{i,t} - v_i\psi_{i,t}$$

Each fleet attempts to obtain the highest possible economic returns from their fishing activity. A measure of these returns is the discounted profit from fishing, *Π*. Profits over a particular period of time are weighted using a discount factor δ that is time independent. In this study, the time period considered when calculating the discounted profits is 15 years which is roughly the time period over which a fishing vessel is utilized.

(1-17) $$\Pi_i = \sum_{t=t_0}^{t_0+14} e^{-\delta(t-t_0)}\pi_{i,t}$$

The control variable is the fishing effort that is exerted during each fishing period. The boundary conditions for the economic exploitation of the fish stocks are given by the population dynamics of the two species that are described earlier.

In the initial model version, the number of vessels in each fleet remains constant. The model used in chapters 5 and 6, however, allows for the entry or exit of vessels, depending on the economic success of the fishery in previous fishing periods. Fleets expand by a given share if the fishery has been profitable over a specified number of previous fishing periods. On the other hand, the number of vessels decreases by the same token if operations were not profitable during the reference period. This way, fleets can reduce costs in economically difficult times or expand fishing effort, if necessary, in periods of particularly good stock development.

1.7.4 Adaptive harvesting strategies of the fishermen

In the model, the fishing effort of each fishing fleet is adjusted after each fishing period according to the returns from fishing in the previous fishing period. This is done by comparing the actual catch size to a previously calculated target value of an expected harvest amount.

The target value of catches is based on the assumption by the fishermen that the growth of the fish stocks follows a logistic function.

$$G_{s,t}^{\exp}\left(B_{s,t}^{init}\right) = g_{s,t}^{\exp} B_{s,t}^{init}\left(1 - \frac{B_{s,t}^{init}}{K_{s,t}}\right) \tag{1-18}$$

G denotes the expected growth of the fish stock, *g* is the rate of reproduction of the fish species and *K* is the environmental carrying capacity. It is assumed that the fishermen know the actual sizes of the stock biomasses *B*. Initial values are set for the rate of reproduction and the environmental carrying capacity. In subsequent fishing periods, these quantities are calculated from the actual development of the fish stocks.

The unit costs, Θ, of exploiting the fish stock that has a known size are given by

$$\Theta_{s,i,t} = \frac{\psi_{s,i}}{q_{s,i} B_{s,t}^{init}} \tag{1-19}$$

Furthermore, it is assumed in the model that the number of fishing fleets and the fleet sizes remain constant over time. Under these conditions it is possible to determine the target value of catches as if the fish stocks were private property, since no new fishing fleets can enter the market. Also, the market prices of cod and capelin are given, and perfect market conditions can be assumed.

The targeted catch size is calculated separately for each fishing fleet. External effects that can arise from competition among the fleets are disregarded. If all these assumptions are considered and all fleets attempt to maximize their economic returns from fishing, the harvesting costs can be related to the growth of the fish stock (Clark, 1990).

(1-20) $$G_{s,i,t}^{'\exp} - \frac{\Theta'_{s,i,t} G_{s,i,t}^{\exp}}{P_{s,i} - \Theta_{s,i,t}} = \delta$$

Substitution of the expressions for stock growth and costs of harvesting the resource leads to an equation that can be used to calculate an optimal size B^* that the fish stock should have in order to maximize the returns from exploiting the resource. If the fish stock is in equilibrium, the target value for the catch size can be determined from the logistic growth function. In that case, the targeted catch size equals the natural growth of the fish stock in that respective fishing period.

At the end of the fishing period the amount of fish landed is compared to the previously calculated target value and the fishing effort is adjusted accordingly. If the actual catch is lower than the target value, the utilization of the fleet needs to be increased in the subsequent fishing period. In the model the increase is set to be 10% of the utilization during the previous fishing season.

When landings equal the targeted catch size the fish stock is actually in equilibrium. The fishing effort in the following fishing period can then be calculated from

(1-21) $$e_{s,i,t+1} = \frac{g_{s,t}^{\exp}}{q_{s,i} v_i} \left(1 - \frac{B_{s,t}^*}{K_{s,t}} \right)$$

If the amount of fish harvested exceeds the previously set target, the utilization of the fishing fleet needs to be reduced in the following fishing period. It is assumed that the reduction constitutes 10% of the former utilization of the fleet.

In addition to the adjustment of the fishing effort after each fishing period, the reproductive rate of the fish stock, which is important for the calculation of the target value of catches, is also updated. This is done on the basis of the actually observed stock sizes. In a first step the “true” rate of reproduction is determined by relating the stock sizes at the beginning of the current and the previous fishing periods.

(1-22) $$\overline{g}_{s,t} = \frac{B_{s,t}^{init} - B_{s,t-1}^{init}}{B_{s,t-1}^{init}}$$

This result is then used in a learning function that is used to determine a weighted average of the actual and previously expected rates of reproduction. This weighted average is then used as a basis for the above calculations in the next fishing period.

(1-23) $$g_{s,t+1}^{\exp} = \lambda_s \overline{g}_{s,t} + \left(1 - \lambda_s\right) g_{s,t}^{\exp}$$

In this expression λ_s is a learning factor which is a measure of the rate of adjustment of the harvest strategy of the different fleets. A large λ_s indicates that the harvesting strategy of the fishermen adjusts quickly to the actual development of the fish stock, whereas a small λ_s suggests slower adaptation of the fishing strategy.

1.7.5 Profit-maximizing harvesting strategies of the fishermen

In this harvesting strategy, fishermen attempt to maximize profits over a number of fishing periods, which is specified prior to the simulation. A short optimization period, e.g. lasting only one year, represents the situation in which the fishermen are sure that their fishing license will be withdrawn in the near future, or that their vessel is depreciated and they have decided to retire. With a longer optimization period, e.g. lasting four or five years, there is a reasonable certainty that fishing will be allowed for some time but not in the long run. A long optimization period of fifteen years resembles the case in which the fishermen are sure that they will be able to harvest for the entire expected lifetime of the vessel.

For all vessel types the sets of fleet utilizations are determined that yield maximum profits for the whole optimization period based on the given stock sizes and population dynamics. The optimal fleet utilization for the current fishing period is applied and the stock information is updated accordingly. The optimization is repeated in each fishing period to account for the actual development of the fish stocks.

Profits are maximized jointly for trawlers and coastal vessels, as regulatory management measures of the cod stock affect both fleet types the same way. Profits from purse seiners used in the capelin fishery are considered separately. The following regulatory management measures are imposed to protect the stocks from overfishing: 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 30% of the stock biomass for cod and 50% for capelin. These parameters have been deduced from past management advice for the stocks.

1.8 Organization of the thesis

1.8.1 Objective

Current climate models suggest that it is possible that there is a shutdown or severe weakening of the THC as a consequence of anthropogenic climate change. Scientists agree that while an actual occurrence of a complete THC breakdown is fairly unlikely, its implications would be widespread and not geographically confined, making a collapse of the THC a ‘low probability – high impact’ event (Rahmstorf, 2000). While climatologists already struggle to quantify the probability of dangerous changes in THC strength really happening, it is even more difficult to scientifically assess the consequences of THC weakening, as impacts range from climatologic and hydrographic changes to ecosystem composition, from energy consumption and utilization of resources to the frequency and spread of diseases.

This thesis focuses on the socioeconomic impacts of a possible THC collapse. First, an integrated assessment model, which is extended to deal with scenarios of THC change, is used to determine the overall extent of monetized impacts. Impacts are calculated on a country level, so that particular impact patterns can be identified on a global scale. The second part of the thesis focuses on a specific economic sector in the geographic region that is expected to be one of the most affected by THC weakening. A bioeconomic model of the Barents Sea fisheries is set up to handle explicit climate change scenarios with an according simulation period. It is the first model that combines the features of short-term economic (optimization) modeling with long-term scenarios of environmental change to assess how much one of the most important marine fisheries worldwide is affected by changes in circulation patterns.

Using scenarios of varying degree of changes in population dynamics or THC weakening, economic success of the fisheries is assessed for different harvesting strategies. Annual profits from fishing are determined for the fleets involved, allowing comparisons of the long-term profitability of the chosen fishing strategy. Population dynamics of the modeled species are considered endogenously in the model, so that dynamic feedbacks on stock development not only stem from the prescribed environmental scenario, but also from the economic utilization by the fishermen.

The results obtained the assessments are not supposed to be understood as precise estimates of the expected economic impacts, as a wide range of possible management measures may have a considerable influence on economic behavior and therefore on economic success despite potentially adverse changes in boundary conditions. However, the analyses serve as a starting point for further explorations of how to devise mitigation or adaptation strategies to deal with a weakening of the THC as successfully as possible.

1.8.2 Structure of the thesis

The thesis consists of two major thematic parts: the assessment of overall socioeconomic impacts of THC weakening and the focus on the marine fisheries in the Barents Sea region. In chapter 2, the scenarios from the *CLIMBER-2* model published in Rahmstorf & Ganopolski (1999) are analyzed with the integrated assessment model *FUND*. The model version used resolves 16 major global economic regions. Simulations cover the time period 2000-2300 and quantify the market and non-market damages in regions deemed most affected by a weakening of the THC.

The *FUND* model is improved for the simulations presented in chapter 3 to resolve the socioeconomic impacts of changes in THC strength on a country level. This time, the average climate impact in each country in the THC breakdown scenario described in Vellinga & Wood (2002) is superimposed on the *FUND* scenario of climate change (Tol, 1999e). Responses to changes in climate conditions can be represented by eight characteristic patterns. Welfare impacts are determined for individual sectors for countries representative of each pattern. Sensitivity analyses of key parameters in the model are conducted to identify sectors that are particularly vulnerable in case of a THC collapse.

The focus shifts to the Arcto-Norwegian cod and capelin fisheries in the Barents Sea in chapter 4. The first version of the bioeconomic model is presented, in which fishermen follow an adaptive harvesting strategy that relates current fishing effort to economic success in the previous fishing periods. Simulations are conducted over a period of 100 years. At the midpoint of each simulation a sudden change in population dynamics occurs. Scenarios consider reductions in productivity or the environmental carrying capacity of varying degree. Profitability of the fisheries in three periods of interest is compared to determine the economic impact of altered population dynamics as they may occur as a consequence of a weaker THC. Sensitivity analyses are performed to assess the influence of the discount rate and the amount of capelin used for human consumption on the harvesting strategies and therefore on returns from fishing.

Chapter 5 extends the analyses with the scenarios used in the previous chapter. Now the model performs non-linear optimizations in order to determine the sets of fishing effort that maximize the fleets’ profits. The entry and exit of vessels as well as management measures to prevent overfishing are implemented in this model version. In the main analyses, an optimization period of 5 years is applied, i.e. the fishing effort is chosen to yield the highest possible profits over five consecutive fishing periods while acknowledging dynamic stock development. The sensitivity analyses are also performed with optimization periods of 1 year and 15 years to explore the influence of future planning of the fishermen on their economic success.

Simulations with the bioeconomic fisheries model coupled to the *CLIMBER-3α* scenarios are performed in chapter 6. The model setup is adjusted to incorporate the influence of temperature and THC strength on recruitment success and natural survival rates of the species. Four scenarios of climate change with various degree of THC weakening are analyzed. Profitability of the fleets is determined for both harvesting strategies. Comparisons of landings and returns from fishing in the scenarios with a stable THC and the THC breakdown scenario yield insights about the success of the fleets and their harvesting strategies in case of altered circulation patterns in the North Atlantic Ocean.

Chapter 7 summarizes the findings, discusses the relevance of the results and points to areas of socioeconomic impact assessment of THC change that may prove worthwhile subjects of further research.

2 Possible economic impacts of a shutdown of the thermohaline circulation: an application of *FUND*

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This chapter was published in *Portuguese Economic Journal*, **3**: 99-114.

2.1 Abstract

Climate change can lead to a substantial reduction of the strength of the thermohaline circulation (THC) in the world oceans. This is often thought to have severe consequences particularly on the North Atlantic region and Northern and Western Europe. The integrated assessment model *FUND* is used to estimate the extent of these impacts. The results indicate that, owing to a slower warming (rather than cooling) of the regions most affected by a THC collapse, climate change induced damages in these regions would be smaller in case of a shutdown of the THC. However, even with a THC collapse, the total and marginal impacts of climate change are negative.

2.2 Introduction

In today’s climate, the North Atlantic region and Northwestern Europe benefit from the heat transported northwards by the thermohaline circulation (THC) in the Atlantic Ocean. This causes this area to be much warmer than comparable regions at the same latitude, with annual mean air temperatures in Scandinavia exceeding the zonal average by more than 10°C (Rahmstorf & Ganopolski, 1999). However, the mechanism that drives the THC is quite sensitive to climatic conditions, and paleoclimatic records suggest that there have been significant fluctuations of the strength of the THC in the past (Dansgaard *et al*., 1993). Periods of extended cooling in the North Atlantic region and Northern and Western Europe can be related to periods of inhibited heat transport to the North in the Atlantic Ocean caused by a shutdown or severe weakening of the THC.

A change of existing climate conditions caused by the continued emission of large amounts of carbon dioxide into the atmosphere from anthropogenic activities will lead to higher global mean temperatures which in turn can result in a weakening or even a complete shutdown of the THC (Manabe & Stouffer, 1993; Rahmstorf & Ganopolski, 1999; Schmittner & Stocker, 1999). The consequences of such a shutdown are manifold: The oceanic uptake of carbon may be reduced (Schmittner & Stocker, 1999), the climate of Northern and Western Europe will be severely affected (Broecker, 1997), and there may be pronounced economic and societal impacts, e.g. caused by decreased agricultural yields and lower landings of the world's high seas fisheries (Rahmstorf, 1997; Keller *et al*., 2000; chapter 4 of this thesis).

The impacts of a possible shutdown of the THC can be analyzed using integrated assessment models. Using the model *DICE* (Nordhaus, 1994), Keller *et al.* (2000) determine the optimal investments and emission paths of anthropogenic carbon dioxide if the THC is supposed to be preserved. Results indicate that emission abatement is only of minor importance if the state of the THC is neglected but becomes an urgent matter if the current state of the THC is to be maintained. Damages related to the collapse of the THC are *assumed* to be slightly less than 1% of the gross world product and can be attributed to a considerable degree to a decreased uptake of carbon dioxide by the ocean and to decreased harvest yields of fisheries that result from pronounced changes in sea-surface temperatures in the world oceans.

In Mastrandrea & Schneider (2001), the *DICE*-model is coupled to a simple climate model that allows for analyses of climate scenarios in which abrupt changes occur endogenously (rather than requiring exogenous climate scenarios, often with only smooth transitions). In this context, the policy relevance of possible abrupt climate changes is addressed. Sensitivity studies with that coupled model show that the incorporation of the possibilities of abrupt future climate change has a profound impact on present and near-term optimal carbon taxes, increasing them by up to an order of magnitude depending on the type of discounting used in the simulation. This highlights the importance of near-term emission reduction since results indicate that it might be impossible to prevent a collapse of the THC despite extensive mitigation measures if they occur too late in time. Mastrandrea & Schneider (2001), like Keller *et al.* (2000), *assume* economic impacts of a THC collapse. In this paper, we *estimate* the economic impacts. We do not do a decision analysis, however.

Climate scenarios of a shutdown of the THC agree that the North Atlantic region and large parts of Europe, but also to some degree the North American continent, would be affected by a considerable cooling over the North Atlantic. Thus, a THC collapse would impact some of the economically most potent regions of the world. Based on climate scenarios from a climate system model of intermediate complexity (*CLIMBER-2*), this study investigates the extent of the overall economic and societal impacts of a possible shutdown or weakening of the THC using the integrated assessment model *FUND*, with a particular focus on the North Atlantic region and the surrounding continents of Europe and North America.

The following section presents the model *FUND* and addresses the extensions of the current version of this integrated assessment model. Section 2.4 looks at the climate scenarios used in this analysis. Section 2.5 presents the results of the simulations of with *FUND*. Section 2.6 discusses the results and concludes the paper.

2.3 The model

This paper uses version 2.8 of the *Climate Framework for Uncertainty, Negotiation and Distribution* (*FUND*). Version 2.8 of *FUND* corresponds to version 1.6, described and applied by Tol (1999a-e, 2001, 2002d), except for the impact module, which is described by Tol (2002b,c) and updated by Tol (2005a). A further difference is that the current version of the model distinguishes 16 instead of 9 regions. The current version of the model also includes diarrhea, not incorporated in earlier versions of *FUND*, as well as a new formulation of the relationship between vector-borne diseases and income growth.

Essentially, FUND consists of a set of exogenous scenarios and endogenous perturbations. The model distinguishes 16 major regions of the world, viz. the United States of America, Canada, Western Europe, Japan and South Korea, Australia and New Zealand, Central and Eastern Europe, the former Soviet Union, the Middle East, Central America, South America, South Asia, Southeast Asia, China, North Africa, Sub-Saharan Africa, and Small Island States. Refer to Appendix 1 for a complete overview of the regions used in *FUND*. The model runs from 1950 to 2300 in time steps of one year. The prime reason for starting in 1950 is to initialize the climate change impact module. In *FUND*, the impacts of climate change are assumed to depend on the impact of the previous year, this way reflecting the process of adjustment to climate change. Because the initial values to be used for the year 1950 cannot be approximated very well, both physical and monetized impacts of climate change tend to be misrepresented in the first few decades of the model runs. The 22nd and 23rd centuries are included to account for the fact that key impacts of a weakening or a shutdown of the THC would be disregarded if the time horizon of the simulations were shorter. Previous versions of the model stopped at 2200.

The period of 1950-1990 is used for the calibration of the model which is based on the *IMAGE* 100-year database (Batjes & Goldewijk, 1994). The climate scenarios for the period 2010-2300 are as used by Rahmstorf & Ganopolski (1999), who follow the IPCC IS92e scenario (Houghton *et al.*, 1995) until 2100, causing a peak of the atmospheric carbon dioxide concentration at roughly 1200 ppmv in 2150. It is further assumed that carbon dioxide emissions are zero as of 2200. Two cases are considered: one in which the THC of the world oceans recovers after a period of weakening and another case in which the THC breaks down almost entirely as a consequence of changes in climatic conditions. The smoothed regional differences between these two scenarios are added to the regional climate changes as generated by *FUND*, using the *FUND* scenario for population, technology and emissions; the *FUND* scenario is close to IS92e until 2100; following Rahmstorf & Ganopolski (1999), emissions are driven to close to zero by 2200.

The scenarios concern the rate of population growth, economic growth, autonomous energy efficiency improvements, the rate of decarbonization of the energy use (autonomous carbon efficiency improvements), and emissions of carbon dioxide from land use change, methane and nitrous oxide.

The scenarios of economic and population growth are perturbed by the impact of climatic change. Population decreases with increasing climate change related deaths that result from changes in heat stress, cold stress, malaria, and tropical cyclones. Heat and cold stress are assumed to have an effect only on the elderly, non-reproductive population. In contrast, the other sources of mortality also affect the number of births. Heat stress only affects the urban population. The share of the urban population among the total population is based on the World Resources Databases (WRI, 2000). It is extrapolated based on the statistical relationship between urbanization and per-capita income which are estimated from a cross-section of countries in 1995. Climate-induced migration between the regions of the world also causes the population sizes to change. Immigrants are assumed to assimilate immediately and completely with the respective host population.

The tangible impacts are dead-weight losses to the economy. Consumption and investment are reduced without changing the savings rate. Thus, climate change reduces the long-term economic growth, although for the short term the consumption is particularly affected. Economic growth is also reduced by carbon dioxide abatement measures.

The energy intensity of the economy and the carbon intensity of the energy supply autonomously decrease over time. This process can be accelerated by abatement policies, an option not considered in this paper.

The endogenous parts of *FUND* consist of the atmospheric concentrations of carbon dioxide, methane and nitrous oxide, the global mean temperature, the impact of carbon dioxide emission reductions on the economy and on emissions, and the impact of the damages to the economy and the population caused by climate change.

Methane and nitrous oxide are taken up in the atmosphere, and then geometrically depleted:

$$C_t = C_{t-1} + \alpha E_t - \beta\left(C_{t-1} - C_{pre}\right) \tag{2-1}$$

where *C* denotes the concentration, *E* the emissions, *t* the year, and *pre* the pre-industrial concentration. Table 2-1 lists the parameters for both gases.

gas	α^a	β^b	pre-industrial concentration
methane (CH_4)	0.3597	1/8.6	790 ppbv
nitrous oxide (N_2O)	0.2079	1/120	285 ppbv

[a] The parameter α translates emissions in millions of metric tons of CH_4 or N_2O into concentrations in parts per billion by volume.

[b] The parameter β determines how fast concentrations return to their pre-industrial (and assumed equilibrium) concentrations;
the reciprocal of β is the atmospheric life time of the gases in years.

Table 2-1: Parameters of equation (2-1) (based on Schimel *et al*., 1996)

The atmospheric concentration of carbon dioxide, measured in parts per million by volume, is derived from a five-box model:

(2-2a)
$$Box_{i,t} = \rho_i Box_{i,t} + 0.000471\alpha_i E_t$$

where

(2-2b)
$$C_t = \sum_{i=1}^{5} \alpha_i Box_{i,t}$$

Here α_i denotes the fraction of emissions *E* (in million metric tons of carbon) that is allocated to box *i* (0.13, 0.20, 0.32, 0.25 and 0.10 respectively) and ρ the rate of decay of the boxes (ρ = exp (- 1 / life time). The life times in the boxes are ∞, 363, 74, 17, and 2 years respectively. This model is based on Maier-Reimer & Hasselmann (1987). Its parameters are taken from Hammitt *et al.* (1992). According to this model, 13 per cent of total emissions remain in the atmosphere indefinitely, while 10 per cent are removed within an average time period of two years.

The radiative forcing of carbon dioxide, methane and nitrous oxide is determined based on Shine *et al.* (1990). The global mean temperature *T* is governed by a geometric build-up to its equilibrium (determined by the radiative forcing *RF*), with a half-life of 50 years. In the base case, the global mean temperature rises in equilibrium by 2.5°C for a doubling of carbon dioxide equivalents, so:

(2-3)
$$T_t = \left(1 - \frac{1}{50}\right) T_{t-1} + \frac{1}{50} \frac{2.5}{6.3 \ln(2)} RF_t$$

Regional temperature follows from multiplying the global mean temperature by a fixed factor, which corresponds to the spatial climate change pattern averaged over 14 GCMs (Mendelsohn *et al.*, 2000). The global mean sea level is also geometric, with its equilibrium level determined by the temperature and a half-life of 50 years. Both temperature and sea level are calibrated to correspond to the best guess temperature and sea level for the IS92a scenario of Kattenberg *et al.* (1996).

The climate impact module is based on Tol (2002b,c). The following impact categories of climate change are considered: agriculture, forestry, sea level rise, cardiovascular and respiratory disorders related to cold and heat stress, malaria, dengue fever, schistosomiasis, diarrhea, energy consumption, water resources, and unmanaged ecosystems.

People can die prematurely due to temperature stress or vector-borne diseases, or they can migrate because of sea level rise. Like all impacts of climate change, these effects are monetized. The value of a statistical life is set to be 200 times the annual per capita income. The resulting value of a statistical life lies in the middle of the observed range of values in the literature (cf. Cline, 1992). The value of emigration is set to be 3 times the per capita income (Tol, 1995, 1996); the value of immigration is 40 per cent of the per capita income in the host region (Cline, 1992). Losses of dryland and wetlands due to sea level rise are modeled explicitly. The monetary value of a loss of one square kilometer of dryland was on average $4 million in OECD countries in 1990 (cf. Fankhauser, 1994). Dryland value is assumed to be proportional to GDP per square kilometer. Wetland losses are valued at $2 million per square kilometer on average in the OECD in 1990 (cf. Fankhauser, 1994). The wetland value is assumed to have logistic relation to per capita income. Coastal protection is based on cost-benefit analysis, including the value of additional wetland lost due to the construction of dikes and subsequent coastal squeeze.

Other impact categories, such as agriculture, forestry, energy, water, and ecosystems, are directly expressed in monetary values without an intermediate layer of impacts measured in their ‘natural’ units (cf. Tol, 2002b).

Climate change related damages can be attributed to either the rate of change (benchmarked at 0.04°C/yr) or the level of change (benchmarked at 1.0°C). Damages from the rate of temperature change slowly fade, reflecting adaptation (cf. Tol, 2002c).

Impacts of climate change on energy consumption, agriculture, and cardiovascular and respiratory diseases explicitly recognize that there is a climatic optimum which is determined by a variety of factors, including plant physiology and the behavior of farmers. Impacts are positive or negative depending on whether the actual climate conditions are moving closer to or away from that optimum climate. Impacts are larger if the initial climate conditions are further away from the optimum climate. The optimum climate is of importance with regard to the potential impacts. The actual impacts lag behind the potential impacts, depending on the speed of adaptation. The impacts of not being fully adapted to new climate conditions are always negative (cf. Tol, 2002c).

Region	Population[a]	Mortality[b]	Morbidity[c]	ΔT[d]	Additional Mortality[e]			Additional Morbidity[f]		
USA	278357	0.041	1.704	3.0	40	(23	70)	1019	(767	1354)
CAN	31147	0.041	1.704	3.7	6	(3	11)	132	(94	185)
WEU	388581	0.015	0.632	2.8	18	(11	31)	506	(387	662)
JPK	173558	0.009	0.166	2.6	5	(3	8)	57	(44	73)
ANZ	22748	0.001	0.083	2.4	0	(0	0)	3	(3	4)
EEU	121191	0.018	0.847	2.9	7	(4	13)	217	(164	287)
FSU	291538	0.122	6.735	3.2	135	(74	244)	4443	(3279	6020)
MDE	237590	0.030	0.166	2.9	24	(14	41)	83	(63	109)
CAM	135222	0.162	0.643	2.2	54	(36	81)	151	(123	185)
LAM	345779	0.168	0.650	2.1	138	(94	202)	381	(313	463)
SAS	1366902	0.229	0.896	2.3	798	(526	1212)	2171	(1755	2687)
SEA	522462	0.135	0.631	1.8	136	(102	182)	492	(424	571)
CHI	1311659	0.033	0.401	3.0	150	(86	261)	1122	(846	1488)
MAF	143482	0.415	0.990	2.9	197	(116	337)	296	(225	389)
SSA	637887	3.167	5.707	2.2	4958	(3321	7404)	6306	(5141	7737)
SIS	44002	0.252	1.092	1.9	23	(17	31)	75	(63	88)

[a] Thousands of people, 2000.
[b] Deaths per thousand people.
[c] Years of life diseased per thousand people.
[d] Regional temperature change for a 2.5˚C global warming.
[e] Additional deaths, thousands of people (67% confidence interval in brackets).
[f] Additional years of life diseased, thousands (67% confidence interval in brackets).

Table 2-2: Diarrhea mortality and morbidity due to a 2.5˚C global warming.

The impacts of climate change on coastal zones, forestry, unmanaged ecosystems, water resources, malaria, dengue fever, and schistosomiasis are modeled as simple power functions. Impacts are either negative or positive, and do not change sign (cf. Tol, 2002c). Diarrhea follows a similar logic (Tab. 2-2). The number of additional diarrhea deaths D^d is given by

$$D_{r,t}^{d} = \mu_r^d P_{r,t} \left(\frac{y_{r,t}}{y_{r,0}} \right)^{\varepsilon} \left(T_{r,t}^{\eta} - T_{r,0}^{\eta} \right) \qquad (2\text{-}4)$$

where P denotes population, y per capita income, and T regional temperature; μ is the baseline mortality, ε (see below) and η=1.14 (with a standard deviation of 0.51) are parameters; r indexes region, and t time. Equation (2-4) was estimated based on the WHO Global Burden of Diseases data (http://www.who.int/health_topics/global_burden_of_disease/en/). Diarrhea morbidity has the same equation as mortality, but with η=0.70 (0.26).

Vulnerability to climate change changes with population growth, economic growth, and technological progress. Some systems are expected to become more vulnerable, such as water resources (with population growth), heat-related disorders (with urbanization), and ecosystems and health (with higher per capita incomes). Other systems are projected to become less vulnerable, such as energy consumption (with technological progress), agriculture (with economic growth) and vector- and water-borne diseases (with improved health care) (cf. Tol, 2002c). Vector-borne diseases fall with economic growth, using a per capita income elasticity of -2.65 with a standard deviation of 0.69.[1] The income elasticity of diarrhea mortality is -1.58 (0.23), for diarrhea morbidity -0.42 (0.12). These elasticities were estimated based on the WHO Global Burden of Diseases data (http://www.who.int/health_topics/global_burden_of_disease/en/).

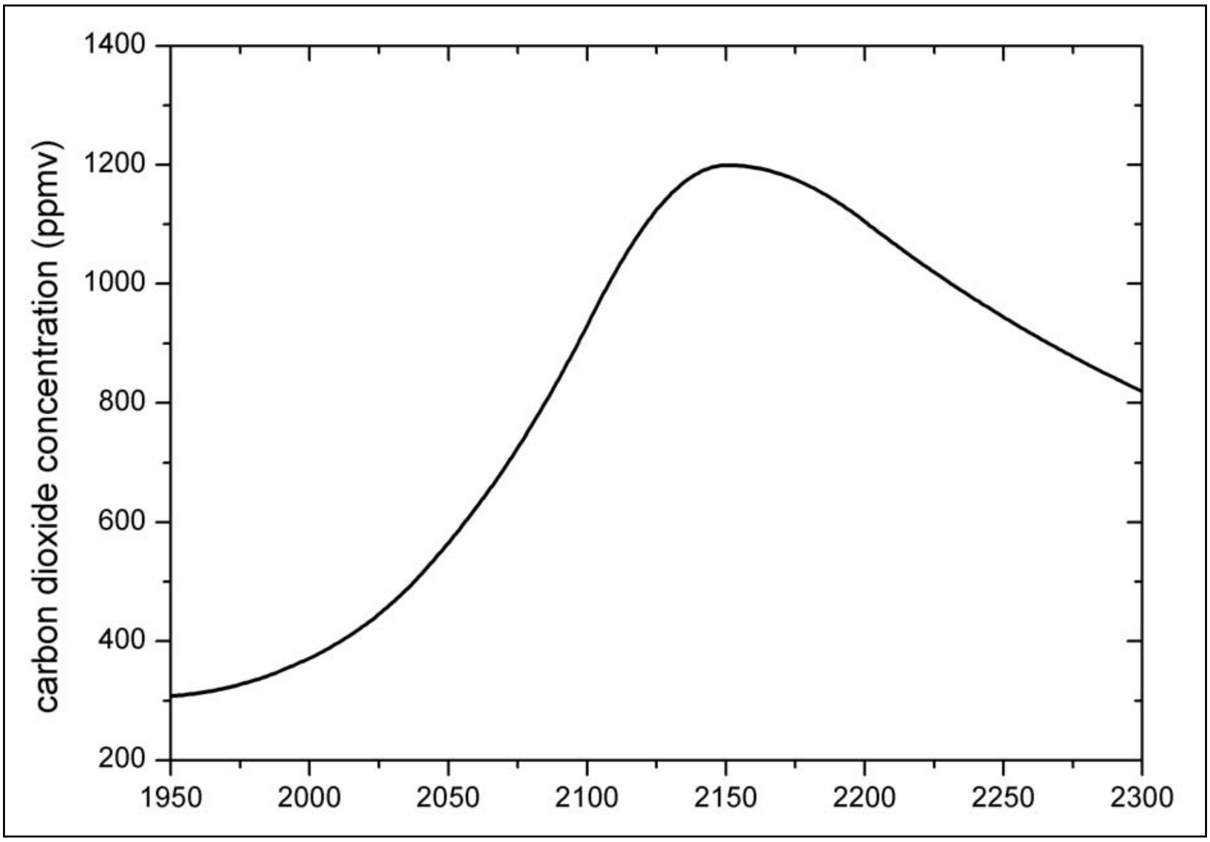

Figure 2-1: Carbon dioxide forcing scenario (based on Houghton *et al.*, 1995).

Carbon dioxide emissions are calculated on the basis of the Kaya identity. Emissions can be modified by political measures, e.g. by a carbon tax. The costs of emission reduction are subject to learning by doing, so that emission abatement in early time periods of the simulations reduces the costs of emission abatement in subsequent periods. The exact

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[1] In previous model versions, vector-borne diseases fall linearly to zero at an annual per capita income of $3100, based on Tol & Dowlatabadi (2001). Increased data availability allowed us to move away from this simple representation.

specification is given by Tol (2005b). The aspect of greenhouse gas emission reduction is not considered in this paper.

2.4 Climate change scenarios

The climate change scenarios used in this study were derived using the climate system model *CLIMBER-2*. The characteristics of this climate model of intermediate complexity are described in detail in Petoukhov *et al*. (2000) and Ganopolski *et al*. (2001). *CLIMBER-2* is particularly useful to assess long-term scenarios that last several centuries up to millennia which have implications on a global scale.

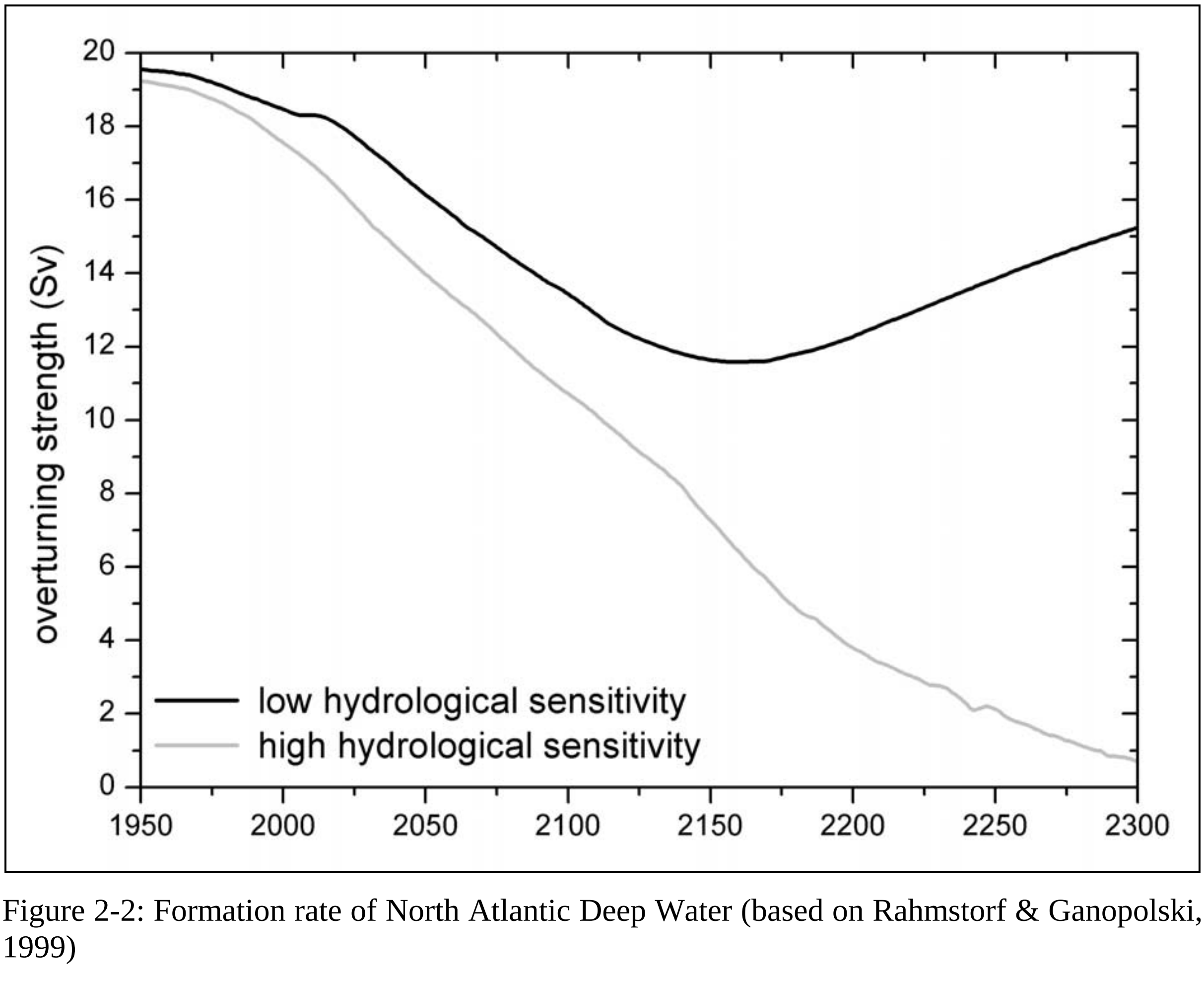

Figure 2-2: Formation rate of North Atlantic Deep Water (based on Rahmstorf & Ganopolski, 1999)

In this analysis, *FUND* is driven with climate scenarios that represent the time period between 1950 and 2300 in the long-term climate development simulated in Rahmstorf & Ganopolski (1999) which is based on radiative forcing as described in the IPCC IS92e scenario (Houghton *et al*., 1995). In this scenario the carbon dioxide concentrations (Fig. 2-1) increase rapidly in the 21st and early 22nd centuries until reaching a peak in 2150 at close to 1200 ppmv. After that a long-term decline of the carbon dioxide concentration in the atmosphere sets in. Two scenarios are considered (Fig. 2-2): one in which the THC weakens during the 21st century by approximately 50 per cent but starts to slowly recover in the 22nd century (low hydrological sensitivity), and another in which the THC breaks down completely by the early 23rd century and does not recover (high hydrological sensitivity).

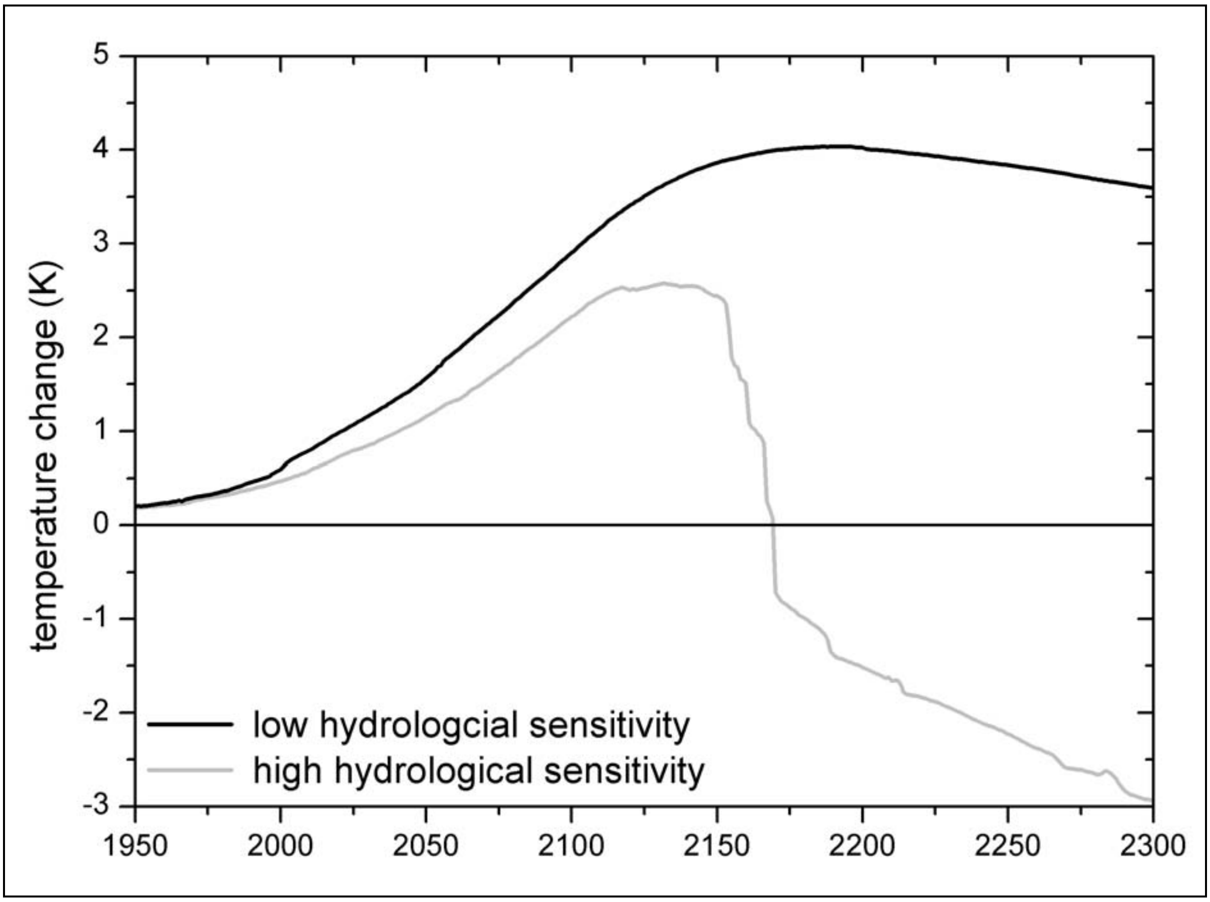

Figure 2-3: Change in winter surface air temperature over the North Atlantic Ocean at 55°N (adapted from Rahmstorf & Ganopolski, 1999)

The global annual mean surface air temperature changes are very similar in both scenarios (Rahmstorf & Ganopolski, 1999), but regional differences are significant. If the THC breaks down completely, the North Atlantic region cools strongly after an initial warming period, with a decline of winter temperatures by more than 4°C from its peak in the early 22nd century to the year 2300 (Fig. 2-3). In contrast, the scenario without a collapse of the THC shows an increase of winter temperatures over the North Atlantic by more than 4°C until a peak in the late 22nd century is reached. After that a slow decline sets in but temperatures always remain much warmer than the initial conditions. The temperature time series were adapted to fit the regions covered by *FUND* and then used to drive the integrated assessment of the development of climate conditions.

2.5 Results

The three regions most affected by a shutdown of the THC are the USA, Canada, and Western Europe. Figure 2-4 displays the climate scenarios for the three regions. It shows that a THC collapse leads to a cooling relative to the base scenario, but not to an absolute cooling; in fact, the shutdown of the THC merely slows warming.

Figure 2-5 displays the market and non-market impacts for the three regions for the scenarios with and without a THC collapse. The market impacts are straightforward in their interpretation. Although *FUND* does recognize that climate change may have beneficial impacts, particularly in developed, temperate countries, these benefits occur only in the first half of the 21st century. After that, global warming has reached a point after which additional warming is generally detrimental. As shown in Figure 4, a collapse of the THC would slow warming, and therefore reduce climate change damages. The reduction of market damages is about 0.5% of GDP in Western Europe, and about 0.4% in the USA and Canada. In fact, the overall impacts on Canada are close to zero with a THC collapse.

Non-market impacts are more complicated, although here as well less warming implies less damage. There is a discontinuity in the non-market damages in the USA; this happens at the point at which the warming trend stops and cooling sets in. Species extinction is assumed to be entirely driven by the absolute value of the rate of climate change, which is zero at that point. This point is brought forward in time by a shutdown of the THC. Western Europe follows the same pattern as the USA, but here the two scenarios almost coincide, whereas Canada shows the same patterns but more pronounced as higher latitudes warm faster.

Discount rate	0 %		1 %		3 %	
	SS	EW	SS	EW	SS	EW
No THC collapse	79.0	170.0	25.2	94.1	5.1	45.1
THC collapse	75.6	167.8	24.4	93.6	5.0	45.0

Table 2-3: Marginal damage costs of climate change ($/t C) with and without a THC circulation collapse, for three alternative discount rates (0, 1 and 3 per cent pure rate of time preference), for simple summation (SS) and equity weighing (EW).

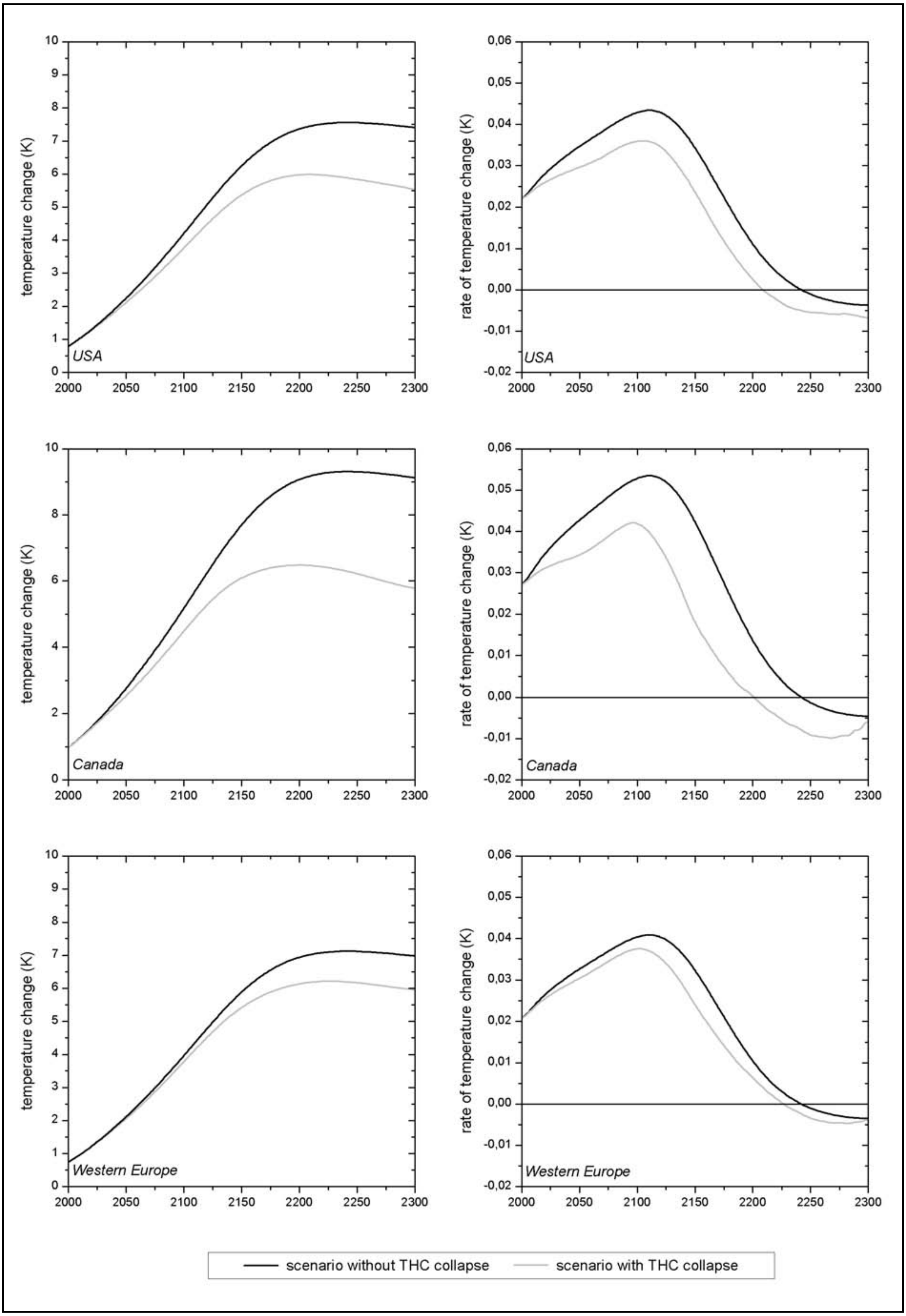

Figure 2-4: The annual mean temperature of the USA (top panel), Canada (middle panel) and Western Europe (bottom panel) in deviation from the pre-industrial temperature (left panel) and the rate of annual temperature change (right panel).

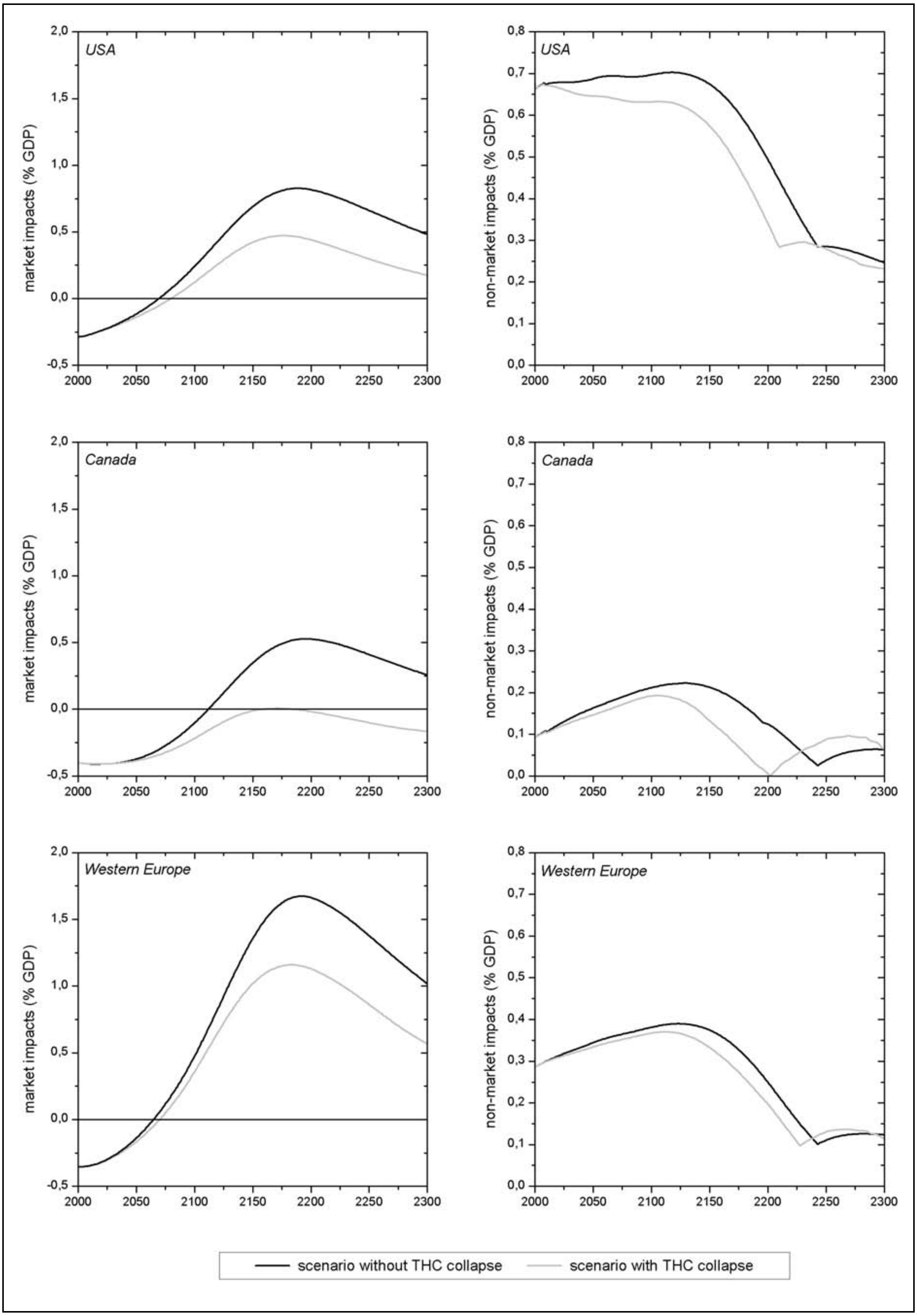

Figure 2-5: The market (left panel) and non-market (right panel) damages of climate change, expressed as a percentage of GDP for the USA (top panel), Canada (middle panel) and Western Europe (bottom panel) with and without a THC collapse.

Table 2-3 shows the marginal damage costs of carbon dioxide emissions. As expected, a collapse of the THC reduces the marginal damage costs, but this reduction is not very pronounced since a THC collapse would only occur near the end of the model duration and discounting – even with a utility discount rate of zero – would weigh that time period less than a time period less far into the future. Another reason is that a collapse of the THC would substantially affect only a certain part of the world.

2.6 Discussion and conclusion

The potential shutdown of the THC is widely seen as a strong reason for greenhouse gas emission reduction. Indeed, a scenario in which Western Europe would rapidly cool to a Canadian climate would be costly for both people and nature. However, this doom scenario seems to be inspired by a comparison of future climate snapshots with and without a THC collapse. If one would place the cooling due to a shutdown of the THC against the background of continuous global warming, the scenario looks less bleak. It should also be considered that the thermohaline shuts down at a time scale that is in the order of decades which is slow compared to the human time scale.

The climate change impacts model used in this study reflects the basic message of the climate change scenarios: As a THC collapse would slow warming, damages would be reduced. From this narrow perspective, a shutdown of the THC is to be welcomed, not to be feared. However, a THC collapse is part of the overall picture of climate change; it is not a separate decision variable. Climate change is a real problem, as both total and marginal impacts are negative, both with and without a THC collapse.

The impact estimates presented here are not complete, and our conclusions are therefore only tentative. A THC collapse would trigger major changes in the ecosystems of North Atlantic Ocean, which would affect commercially valuable fish stocks, such as cod, and species important to biodiversity and nature protection, such as whales. This is not included in the model. Furthermore, we use a geographical resolution that is coarse. For instance, we estimate the effects for Western Europe as a whole, while the impact of a THC collapse on Iceland, Ireland and Norway would be much more severe than on Greece and Italy. Finally, we compare single realizations of scenarios with and without a THC collapse. One reason to worry about a THC collapse is that it is a regime change, and the uncertainties around the state of the natural system are much greater than without a THC collapse. All these things are subjects for future research.

2.7 Appendix: The regions in *FUND*

Acronym	*Name*	*Countries*
USA	USA	United States of America
CAN	Canada	Canada
WEU	Western Europe	Andorra, Austria, Belgium, Cyprus, Denmark, Finland, France, Germany, Greece, Iceland, Ireland, Italy, Liechtenstein, Luxembourg, Malta, Monaco, Netherlands, Norway, Portugal, San Marino, Spain, Sweden, Switzerland, United Kingdom
JPK	Japan and South Korea	Japan, South Korea
ANZ	Australia and New Zealand	Australia, New Zealand
CEE	Central and Eastern Europe	Albania, Bosnia and Herzegovina, Bulgaria, Croatia, Czech Republic, Hungary, FYR Macedonia, Poland, Romania, Slovakia, Slovenia, Yugoslavia
FSU	Former Soviet Union	Armenia, Azerbaijan, Belarus, Estonia, Georgia, Kazakhstan, Latvia, Lithuania, Moldova, Russia, Tajikistan, Turkmenistan, Ukraine, Uzbekistan
MDE	Middle East	Bahrain, Iran, Iraq, Israel, Jordan, Kuwait, Lebanon, Oman, Qatar, Saudi Arabia, Syria, Turkey, United Arab Emirates, West Bank and Gaza, Yemen
CAM	Central America	Belize, Costa Rica, El Salvador, Guatemala, Honduras, Mexico, Nicaragua, Panama

SAM	South America	Argentina, Bolivia, Brazil, Chile, Colombia, Ecuador, French Guiana, Guyana, Paraguay, Peru, Suriname, Uruguay, Venezuela
SAS	South Asia	Afghanistan, Bangladesh, Bhutan, India, Nepal, Pakistan, Sri Lanka
SEA	Southeast Asia	Brunei, Cambodia, East Timor, Indonesia, Laos, Malaysia, Myanmar, Papua New Guinea, Philippines, Singapore, Taiwan, Thailand, Vietnam
CHI	China plus	China, Hong Kong, North Korea, Macau, Mongolia
NAF	North Africa	Algeria, Egypt, Libya, Morocco, Tunisia, Western Sahara
SSA	Sub-Saharan Africa	Angola, Benin, Botswana, Burkina Faso, Burundi, Cameroon, Cape Verde, Central African Republic, Chad, Congo-Brazzaville, Congo-Kinshasa, Cote d’Ivoire, Djibouti, Equatorial Guinea, Eritrea, Ethiopia, Gabon, Gambia, Ghana, Guinea, Guinea-Bissau, Kenya, Lesotho, Liberia, Madagascar, Malawi, Mauritania, Mozambique, Namibia, Niger, Nigeria, Rwanda, Senegal, Sierra Leone, Somalia, South Africa, Sudan, Swaziland, Tanzania, Togo, Uganda, Zambia, Zimbabwe
SIS	Small Island States	Antigua and Barbuda, Aruba, Bahamas, Barbados, Bermuda, Comoros, Cuba, Dominica, Dominican Republic, Fiji, French Polynesia, Grenada, Guadeloupe, Haiti, Jamaica, Kiribati, Maldives, Marshall Islands, Martinique, Mauritius, Micronesia, Nauru, Netherlands Antilles, New Caledonia, Palau, Puerto Rico, Reunion, Samoa, Sao Tome and Principe, Seychelles, Solomon Islands, St Kitts

	and Nevis, St Lucia, St Vincent and Grenadines, Tonga, Trinidad and Tobago, Tuvalu, Vanuatu, Virgin Islands

3 The economic impact of a shutdown of the thermohaline circulation: an extended application of *FUND*

P. Michael Link & Richard S.J. Tol

This chapter has been submitted for publication.

3.1 Abstract

The integrated assessment model *FUND 2.8n* is applied in an analysis of the overall economic consequences in a scenario of a shutdown of the thermohaline circulation (THC). Monetized market and non-market impacts of changes in environmental conditions following a THC collapse are determined for 207 individual countries. Eight different response patterns can be identified. The dominant pattern is that a THC shutdown has an offsetting effect on the underlying warming trend. Depending on whether the impacts of warming are initially beneficial or detrimental, the economic effects of a THC collapse show distinct regional variability. Key economic sectors affected in a THC shutdown scenario are water resources and energy consumption, as well as cardiovascular and respiratory diseases among health impacts. The maximum, national impact of a collapse of the THC turns out to be of the magnitude of a few per cent of GDP, but the global impact is much smaller. Considering the low probability of occurrence, a THC shutdown does not call for drastic action at present.

3.2 Introduction

The potential weakening of the thermohaline circulation (THC) because of climate change has captured the public mind. Often referred to as a collapse of the ocean conveyer belt that brings warmth to Europe, the public picture is one of an impending ice-age. More sophisticated analysts and policy makers worry about the unprecedented impacts this scenario of climate change would have. As is all too often the case, these impacts are speculative – not based on any impact model, in fact not even on the best guesses of impact experts. In this paper, we offer estimates of the impacts of a shutdown of the THC.

This paper extends chapter 2 of this thesis and Ceronsky *et al.* (2005). In the previous chapter, we use *FUND 2.8* to estimate total impacts and compare two scenarios: one without and one with a THC collapse. No sensitivity analysis was reported, indeed done. In Ceronsky *et al.* (2005), *FUND 2.8* was also used to estimate marginal impacts. The THC scenario applied is but one in a whole range of extreme climate scenarios. Both papers conclude that a THC shutdown is not at all dramatic; it may even be beneficial as warming slows down but does not turn into cooling. Both papers have the distinct disadvantage that the spatial resolution is crude. Iceland, Ireland, and Norway, the countries most at risk of a THC shutdown, are grouped with Western Europe – when Iceland and Greece are averaged, any effects get lost in the aggregation. In the current paper, we use *FUND 2.8n*, and study each country separately.

3.3 The model

The *FUND* model has been used for many purposes, but its main strength has always been the impacts of climate change. Earlier versions had 9 regions, and later versions 16. In this paper, we discard most of the model, and only retain the impact module. This part, however, is reparameterized for 207 countries. The impact module of *FUND 2.8* is described extensively in Tol (2002b, 2002c). However, the data presented in those studies were aggregated to a regional level. For some impacts, this was just a summation of country-based data. For other impacts, only regional information was available. We now present the national impacts module of *FUND 2.8n*. The source code, in Excel, can be found at http://www.uni-hamburg.de/Wiss/FB/15/Sustainability/fund28n.zip .

The climate change induced impact on cardiovascular mortality is based on Martens (1998). Impacts are assumed to vary linearly with the deviation of the actual temperature in hottest or coldest month (for heat- and cold-related cases, respectively) from the temperature that the population is acclimatized to. The latter increases with warming too, using a geometric update procedure of the temperature, in which the gap closes by 10% per year. Thus, the impact is more than linear in the rate of warming[1]. Heat- and cold-related cases are modeled separately, as are effects on people below and above 65 years of age. Heat-related cardiovascular

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[1] In the regional version of *FUND*, cardiovascular and respiratory impacts are quadratic in the level of temperature, but insensitive to the rate of warming. Intraregional variation does not allow for consistent parameterization with acclimatization.

disorders are assumed to be an urban phenomenon only. Respiratory mortality is treated in the same way as heat-related cardiovascular disorders, but is not limited to urban areas.

Schistosomiasis, dengue fever and malaria are assumed to be linearly related to warming. The vulnerability is based on the 1995 data in WHO (1995). Vulnerability is assumed to decline with per capita income growth, with an elasticity of 2.65. Diarrhea mortality is more than linear in warming with a power of 1.14, while vulnerability falls with an income elasticity of 1.58. Diarrhea morbidity follows the same pattern, but with different parameters: 0.70 for the climate effect, and 0.42 for the income effect.

For all diseases except diarrhea, morbidity is assumed to be proportional to mortality, using the ratio given in WHO (1995). Mortality is valued at 200 times the annual per capita income of each deceased, morbidity at 0.8 times the annual per capita income of the diseased.

Cooling demand is based on Downing *et al.* (1995, 1996), who report regional results only. Impacts are assumed to be more than linear in warming, with a power of 1.5, and to increase with economic growth with an elasticity of 0.8. This income elasticity is used to downscale regional sensitivities to a national level. Heating demand is based on the same source and follows the same procedure, but the sign is opposite and it is less than linear in warming with a power of only 0.5. Water resources are also based on Downing *et al.* (1995, 1996). Impacts are assumed to change linearly with global warming; the assumed income elasticity is 0.85.

Species loss varies quadratically with the rate of warming. The value of species loss is logistic in the rate of warming. The maximum amount that people are willing to pay to prevent climate change-induced species loss is set to be $50 per person per year for people with the average income in the OECD in 1990. This maximum is proportional to income, and inverse proportional to the number of remaining species. Poorer countries approach the maximum logistically as they grow richer.

The impacts of sea level rise are derived from Hoozemans *et al.* (1993) and Bijlsma *et al.* (1996). There are no more recent global impact studies; see Nicholls and Tol (forthcoming) for a current review. Without coastal protection, wetland and dry land losses are assumed to be linearly related to sea level rise. Dry land losses decline linearly with protection, but wetland losses increase linearly with protection. The costs of dry land loss change linearly with per capita income and population density. The value of wetland losses follows the same logic as the value of species loss. Protection costs are assumed to be constant. The level of protection is set by a cost-benefit analysis, based on Fankhauser (1994), trading off the benefits of less dry land loss against the costs of protection and additional wetland loss. Dry land loss induces migration. Relocation is assumed to occur domestically. The cost of migration is assumed to equal 3.4 times the per capita income (Tol, 1995).

The impacts of climate change on agriculture are calibrated to Darwin *et al.* (1995), Fischer *et al.* (1996), Kane *et al.* (1992), and Tsigas *et al.* (1996). The impacts are split into three parts. The first part is linearly related to the rate of warming. These impacts are always negative. The second part is quadratic, with an explicit climate optimum for agriculture for each country. Impacts are positive (negative) if a country moves towards (away from) its optimum. The third part is logarithmic in the atmospheric concentration of carbon dioxide. The national parameters equal the parameters of the region to which the country belongs in *FUND 2.8*. However, the climate scenario analyzed is resolved at country level. Impacts are expressed as fraction of national agricultural production. The share of agriculture in GDP is country-specific. It falls with an income elasticity of 0.31.

Climate change impacts on forestry are calibrated to Perez-Garcia *et al*. (1996) and Sohngen *et al*. (2001). Impacts are assumed to vary linearly with warming and logarithmically with the atmospheric concentration of carbon dioxide, each with a weight of one half. Sensitivities decrease with economic growth with an income elasticity of 0.31. This elasticity was used to downscale regional to national sensitivities.

3.4 Scenarios

The analysis of the impacts of a shutdown of the THC is based on the hosing experiment of Vellinga and Wood (2002), which was conducted using the *HadCM3* model (Gordon *et al.*, 2000), where the THC collapsed after one strong pulse of freshwater was added in year 2100. After that the simulation covered another century in which the THC could recover to some extent. In our assessment, we use the difference of the average temperature per country in the time period 2100 through 2129 between the *HadCM3* hosing scenario and a control run with stable climate conditions (Fig. 3-1).

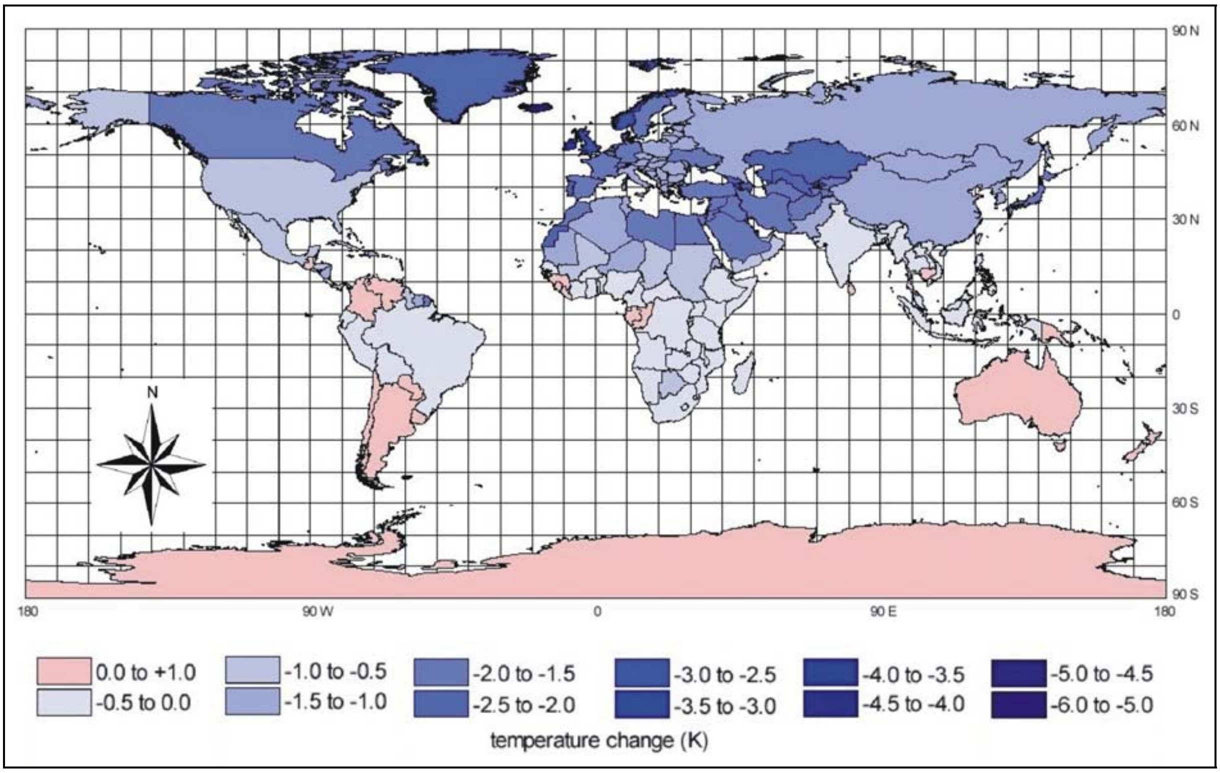

Figure 3-1: The difference of the 2100-2129 average annual temperature between the *HadCM3* THC shutdown scenario and the control scenario.

We superimpose the difference on a *FUND* scenario of climate change, using a spatial pattern that is calibrated to the *HadCM3* model. The *FUND* scenario of climate change (Tol, 1999c) follows the IPCC IS92a scenario (Leggett *et al.*, 1992) for the economic and demographic development, and the emissions trajectory of the IS92f scenario. In this analysis, it is assumed that the THC functions until 2070. After that, it slows down. In 2100, the full climate effect of the THC shutdown is assumed to take hold. The transition from 2070 to 2100 between the two states of the THC is linear.

3.5 Results

Starting from present, the simulation extends through the 21st century. The market and non-market impacts of climate change are determined for the year 2100 and related to the initial conditions. Figure 3-2 shows the impact of the THC shutdown in 2100. The impact is measured as the difference between the monetized impact of climate change with and without a THC shutdown. Eight different situations can be distinguished.

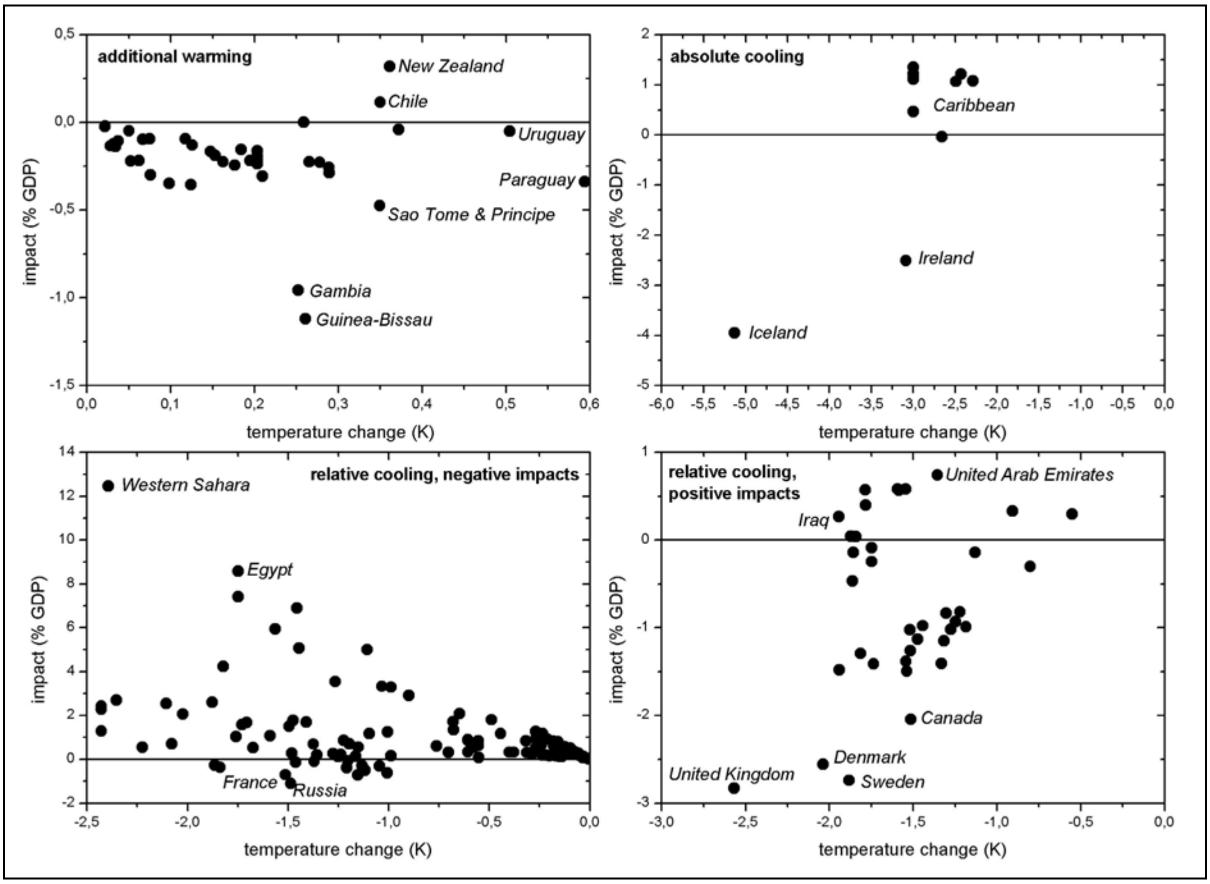

Figure 3-2: The effect per country of a shutdown of the thermohaline circulation on the welfare impacts of climate change in 2100. In the top panels, countries warm faster (left panel) or cool (right panel). In the bottom panels, countries warm slower. The bottom left panel displays countries that benefit from climate change, the bottom right panel countries that are damaged by climate change.

In some places, a THC shutdown implies additional warming (1). If warming is already negative without a change in THC strength, additional warming is worse, and a THC shutdown has a negative impact (1N). This is the case in West-Africa. Figure 3-3 shows the welfare impacts in Gambia as an example. If warming is generally positive, additional warming induced by a THC change is even better, and a THC shutdown has a positive impact (1P). This is the case for Australia and New Zealand (Fig. 3-3).

In some places, a THC shutdown implies absolute cooling (2). In temperate or subarctic countries, further cooling has negative impacts (2N). This is the case in Ireland and Iceland (Fig. 3-3). In subtropical or tropical countries, cooling has positive impacts that can be quite substantial in some countries (2P). This is the case in the Caribbean. Figure 3-3 shows results for Barbados as an example.

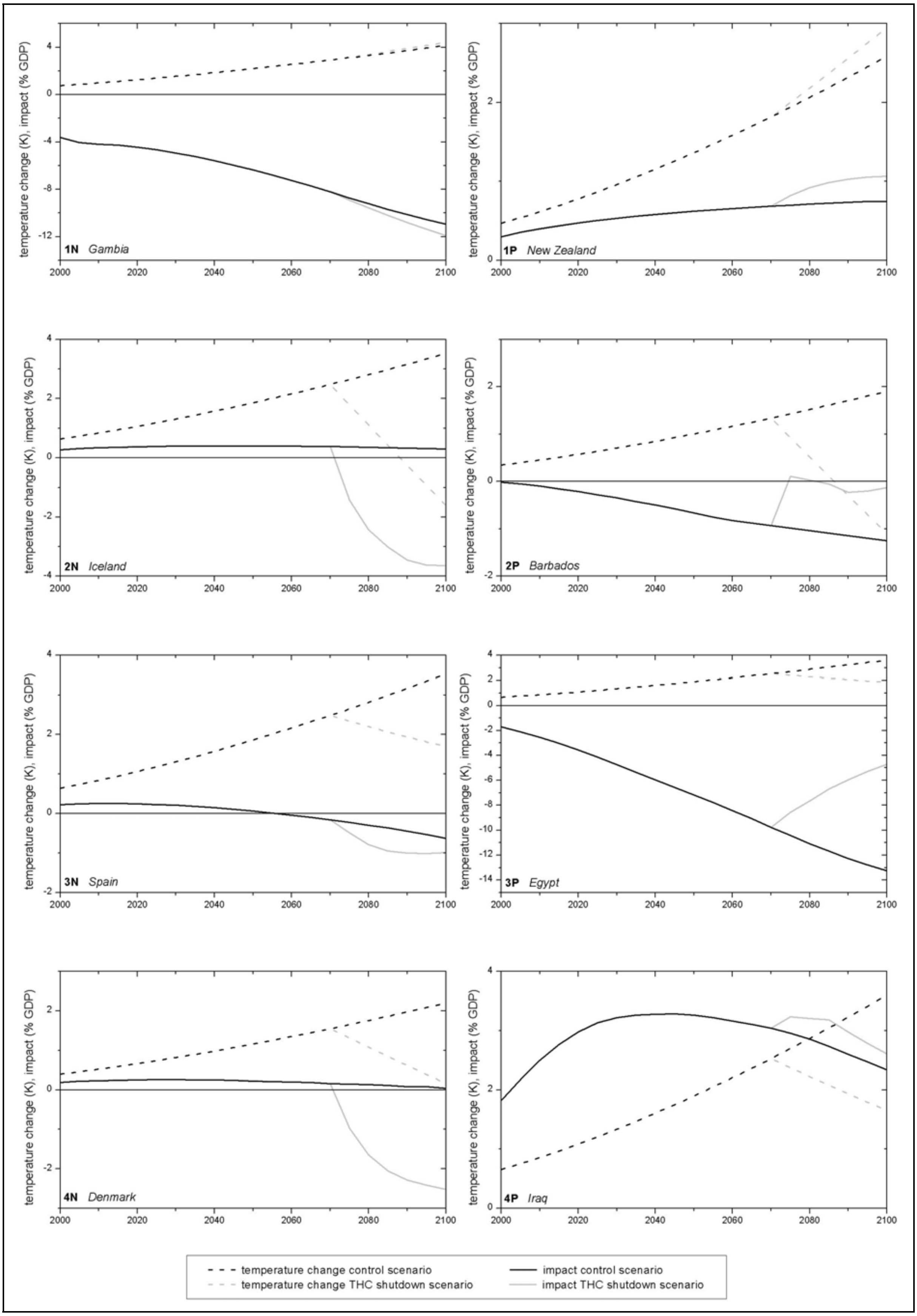

Figure 3-3: The welfare impacts of climate change with and without a thermohaline circulation shutdown for eight countries. The solid lines denote welfare impacts (left axis), the dashed lines temperature change (right axis).

So far, the emerging pattern has been straightforward. However, in many countries the development is not as simple. It is often the case that a THC shutdown has an offsetting effect on a regional warming trend (3). If the impacts of climate change are negative to start with, one would expect a shift toward the better resulting from slower warming (3P). This is indeed the case in most countries. Figure 3-3 shows Egypt as an example. There are a few exceptions, however, e.g. France, Russia, and Spain (Figure 3-3). The reason is that without a THC shutdown, the decreasing number of cold-related cardiovascular deaths resulting from warmer conditions contributes significantly to positive welfare impacts. With a THC shutdown, this effect disappears, and the overall impacts become much more negative (3N).

If the impacts of climate change are positive without any change in THC strength, one would expect a worse overall impact as a consequence of slower warming (4). Again, this is the case in many countries. Figure 3-3 shows Denmark as an example (4N). Here, the positive effect of global warming is not only weakened but reversed completely as the THC shutdown brings about considerable economic damages. However, there are exceptions to this development as well, e.g. in Iraq (Fig. 3-3). There, a weakening of the THC is actually initially beneficial, but the positive effect of a collapsed THC disappears over time as the difference in climate-related economic impacts between the THC shutdown scenario and the control run diminishes (4P).

Figure 3-4 shows the impact per sector of a THC shutdown in 2100 for the eight selected countries. The most important impacts of a THC shutdown are on human health, energy consumption, and water resources, with impacts on ecosystems playing a smaller role. The impact on agriculture and sea level rise is negligible.

Figure 3-5 depicts the impact of a change in THC strength aggregated to a global level by adding dollars without correcting for inequity aversion (Fankhauser *et al.*, 1997, 1998). At this highly aggregate level, the differences seen in Figures 3-3 and 3-4 are obviously hidden. The dominant pattern resembles that of Spain. Climate change first brings benefits, but the benefits start to decline after 2015, and turn into damages in 2060. A THC shutdown would bring about additional damages. The gap between the two scenarios widens rapidly, as the health benefits of warmer climates disappear. The gap then narrows again as the benefits of slowed warming become more important at the end of the simulation period.

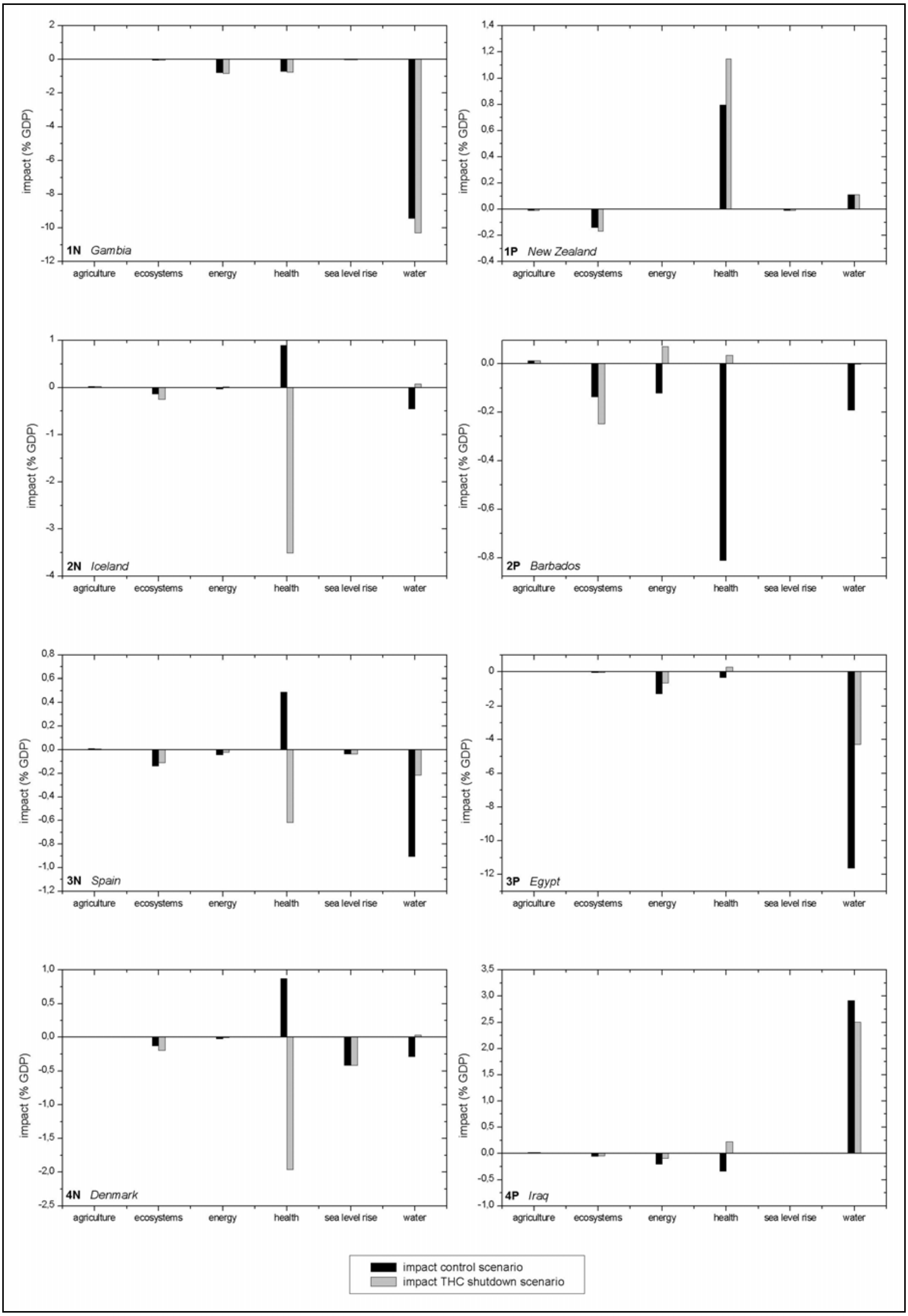

Figure 3-4: The welfare impacts of climate change in 2100 with and without a thermohaline circulation for eight countries per sector.

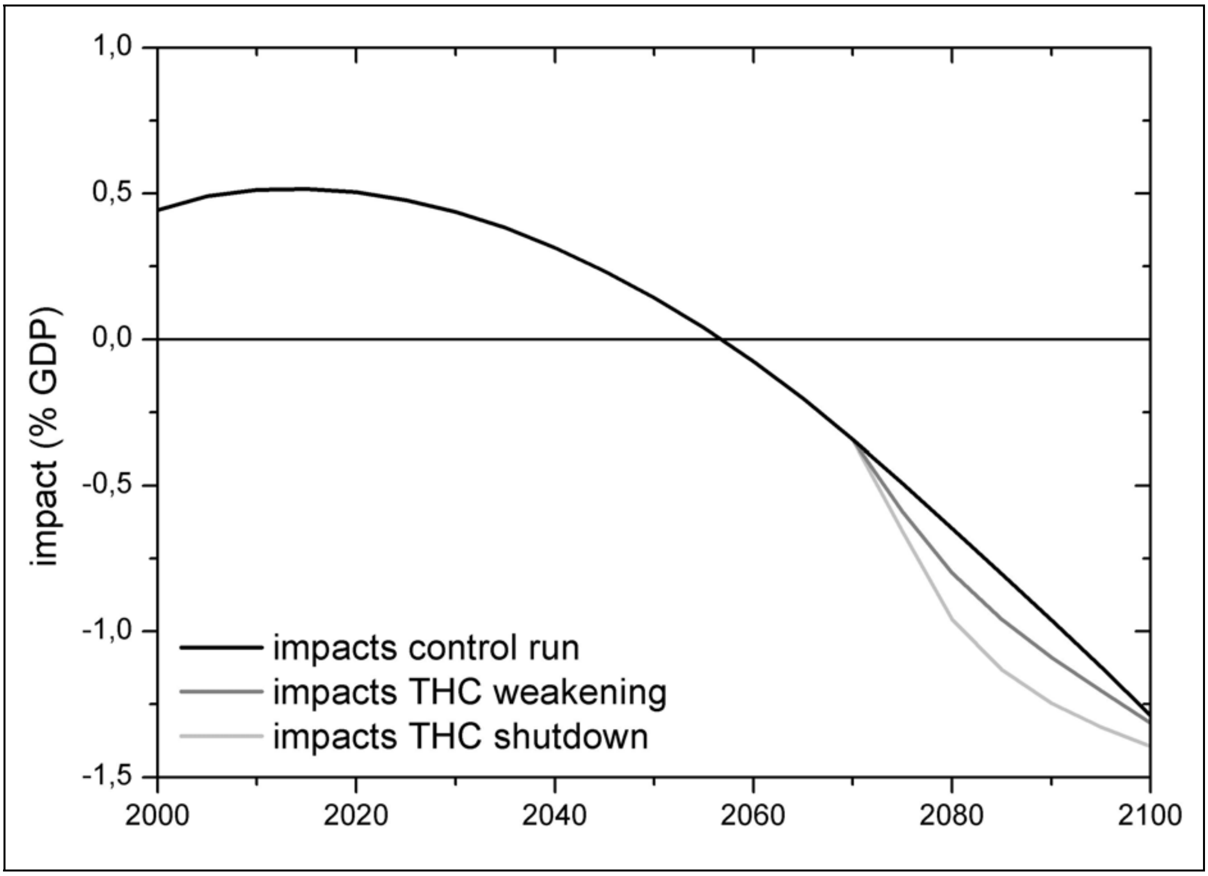

Figure 3-5: The global welfare impacts of climate change for scenarios with no impact on the thermohaline circulation, a slowdown, and a shutdown.

3.6 Sensitivity analysis

In the analysis presented above, there are many assumptions about the parameters in *FUND 2.8n*, the scenarios that drive the model, and the shutdown of the THC. Some of these assumptions have little influence on the results. Other assumptions are very important. In this section, we report sensitivity analyses on the key parameters.

One of the crucial inputs is the assumed climate change due to the shutdown of the THC. Table 3-1 shows the 2100 welfare impacts for eight selected countries for the base scenario (no effect on the THC), the scenario used in Section 4 (THC shutdown), and a scenario halfway in between (THC slowdown). The eight selected countries are representative for the variety of responses observed. In a few countries, such as Spain, a slowdown of the THC has a positive effect, but a shutdown has a negative effect. In a larger number of countries, such as Denmark and Iceland, a weakening of the THC to half of its original strength leads to less than half the impact of a complete shutdown. Figure 3-5 shows that this is the dominant pattern at the global level. Furthermore, unreported experiments show that this impact pattern also holds for a weaker slowdown of the THC. In other countries, such as Egypt, Gambia and New Zealand, the response is approximately linear. There are some countries, such as Iraq, in which the response is less than linear. In most of those countries, the impact of a slowdown is positive; and although the overall effect of a shutdown of the THC is still positive, the positive impacts begin to saturate while the negative impacts start to escalate. It is therefore no surprise that there are a few countries, such as Barbados, in which the difference between no change and a slowdown of the THC is positive, while the difference between slowdown and a shutdown is negative, even though the difference between no change and a THC shutdown is positive.

	Impact (% GDP) control scenario	Impact (% GDP) THC weakening	Impact (% GDP) THC shutdown
1N Gambia	-10.94	-11.42	-11.90
1P New Zealand	0.75	0.91	1.07
2N Iceland	0.30	-1.44	-3.65
2P Barbados	-1.25	0.22	-0.13
3N Spain	-0.62	-0.55	-0.99
3P Egypt	-13.27	-8.94	-4.69
4N Denmark	0.04	-1.04	-2.52
4P Iraq	2.34	2.53	2.61

Table 3-1: The welfare impact of climate change in 2100 on selected countries for scenarios with no impact on the thermohaline circulation, a slowdown to 0.5 THC_{init}, and a complete shutdown.

	Impact (% GDP) control scenario	Impact (% GDP) THC shutdown	Difference (% GDP)
Base	1.29	1.39	0.10
Water: Sensitivity	1.31	1.42	0.11
Water: Income elasticity	1.23	1.35	0.12
Heating: Sensitivity	0.49	0.73	0.24
Heating: Non-linearity	0.56	0.96	0.40
Heating: Income elasticity	1.59	1.65	0.06
Cooling: Sensitivity	3.48	2.93	-0.55
Cooling: Non-linearity	0.23	0.73	0.50
Cooling: Income elasticity	0.44	0.80	0.36
Respiratory	1.40	1.39	-0.01
Cardiovascular, heat	1.66	1.51	-0.15
Cardiovascular, cold	0.54	1.36	0.82
Urbanisation	1.33	1.41	0.08
Aging	1.21	1.43	0.22
Value of a statistical life	0.72	1.60	0.88
Value of a year disabled	1.33	1.43	0.10

Table 3-2: The global welfare losses of climate change in 2100 with and without a thermohaline circulation shutdown for a range of parameter choices.

Table 3-2 shows a sensitivity analysis of the parameters that govern the estimated impacts on water resources, energy consumption, and cardiovascular and respiratory diseases. If either the sensitivity of water resources to climate change or the income elasticity is doubled, damages vary only slightly, and the impacts of a THC shutdown are just a little worse than in the reference scenario.

A doubling of the sensitivity of heating energy causes damages to decrease because savings on heating are beneficial; however, the temperature change due to a THC shutdown becomes more important as the world cools. If heating were linearly related to temperature, rather than the square root as in the base scenario, the result would be qualitatively the same. The opposite effects are observed when the income elasticity is doubled so that future energy use for heating is smaller. Doubling the sensitivity of cooling energy leads to increased damages both due to climate change and due to a THC shutdown. If cooling changed linearly with temperature, rather than proportional to the 1.5th power of the temperature as in the base case, damages would fall in both scenarios, but less in the scenario with the THC shutdown, so that the difference between the scenarios increases over time. The same pattern is observed for a doubling of the income elasticity, which causes energy use for cooling to decrease over time.

A twofold increase of the sensitivity of heat-related cardiovascular or respiratory mortality causes climate change impacts to increase. A THC shutdown would have positive effects, as warming is less pronounced. If the sensitivity of cold-related cardiovascular mortality is doubled, the opposite pattern can be observed. A doubling of the rate of urbanization leads to higher climate change impacts as the number of heat-related deaths rises; by the same token, the effect of a THC shutdown is reduced. A doubling of the rate of aging has the opposite effect, by particularly increasing cold-related cardiovascular mortality. Doubling the value of a statistical life reduces the impact of climate change because of the higher weight placed on the avoided cold-related deaths in the rich and temperate countries. These benefits disappear with a THC shutdown.

3.7 Discussion and conclusion

In this paper, we present estimates of the welfare losses incurred from a rapid shutdown of the THC. In some places, a THC shutdown reduces the rate of warming, and this may well be a benefit. This effect dominates the result presented in chapter 2 of this thesis. However, the previous assessment ignored the additional warming in some parts of the world that are here shown to have mostly negative impacts. Furthermore, the crude spatial resolution of the first *FUND* analysis did not allow the investigation of places where a THC shutdown would lead to an absolute cooling, rather than slowed warming. Absolute cooling also increases damages. Finally, at the finer spatial scale used here, health impacts are modeled in a more realistic way – particularly, a shutdown of the THC leads to a considerable change in cold-related cardiovascular mortality.

Overall, we find that a THC shutdown has a negative effect on welfare; the same is true, but to a lesser extent, for a THC slowdown. The best guess estimate is –0.1% of global GDP for a THC shutdown. Sensitivity analyses show estimates in the range of –0.9% GDP to +0.6% GDP. National impacts are, of course, much larger, but do not exceed a few percent of GDP. However, it has to be noted that the THC scenario used in this paper is rather unlikely. Based on the small overall impacts of a shutdown of the THC and the low probability of occurrence, no drastic action is currently necessary to deal with possible consequences of a THC shutdown.

The results presented here are obviously specific to the model and scenario chosen. The *HadCM3* scenario is not untypical; it is the only model for which we could obtain both a warming scenario and a THC scenario. Other modeling teams should report results from their model. However, since the THC scenario is moderate over land, other impact models would have to be very nonlinear to lead to drastically different results than *FUND 2.8n*.

Fisheries are omitted from this analysis. However, fisheries are only a small part of the world economy – and therefore do not bias the global results much. On the other hand, fisheries are important for the economy of some countries that are considerably affected by a collapse of the THC, e.g. Iceland or Scandinavian countries such as Denmark and Norway; therefore, some of our national results may be biased. Assessments of the development of the Barents Sea cod fishery in scenarios of global warming with and without a collapse of the THC show that fisheries benefit from increased reproductive success and stock growth due to temperature increases of the cod spawning grounds (see chapter 4 of this thesis). This positive effect is somewhat offset if the THC breaks down, but the overall economic consequences remain rather limited.

Similarly, tourism is omitted. Here, impacts mostly consist of redistribution, so the global impact would not be affected much; however, with climate change, the cool countries in the North Atlantic region would become more popular destinations of summer tourism (Hamilton *et al.*, 2005), and may lose that advantage with a THC shutdown. Most importantly, *FUND 2.8n* does not consider precipitation. The bias thus introduced is of unknown sign and size. Our results should be interpreted with the necessary caution. Future research should address these caveats.

Nonetheless, our estimate is that the global economic impact of a THC shutdown is limited. Combined with a low probability, there is little reason for concern. The national results are larger. Note that the THC shutdown is the only aspect of climate change, so far, for which the impacts are larger in rich and temperate countries. The policy implications arising from this fact are also subject of future research.

4 Economic impacts of changes in the population dynamics of fish on the fisheries of the Barents Sea

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This chapter was published in *ICES Journal of Marine Science*, **63**: 611-625.

4.1 Abstract

A bioeconomic simulation model of the two interacting fish species cod (*Gadus morhua*) and capelin (*Mallotus villosus*) and their fisheries is presented and applied to assess the consequences of changes in the population dynamics of these important fish stocks in the Barents Sea. In each scenario, the population dynamics of the fish species are changed by reducing the reproduction-induced productivities and/or the carrying capacities. Stock sizes and landings of fish are calculated for each fishing period, and the net present values of profits from fishing are determined for time periods prior to and after the change in population dynamics. Results show that reduced growth rates or carrying capacities lead to lower stock levels and consequently to smaller catches. There is only a small short-term economic impact on the fisheries, but the long-term consequences are pronounced. In some cases, greater fishing activity in the first few years after the change in population dynamics causes harvests to remain stable despite diminishing stock sizes. This stabilizes the returns from fishing in the short term, but veils the apparent negative long-term impact on the fisheries resulting from adversely affected stock dynamics.

4.2 Introduction

The size and the geographic range of fish stocks depend largely on existing hydrographic conditions. Changes in temperature, salinity, or oxygen content can have adverse effects on the fish stock population dynamics, sometimes even causing stocks to collapse, especially when they are subjected to fishing. Therefore, it is important in an assessment of the population dynamics of fish stocks not only to consider economic exploitation, but also to allow for sudden changes brought about by altered climatic and oceanographic conditions. While the models currently used to assess fish stocks account for a variety of environmental conditions as well as effects of changes in different compartments of the ecosystem, such as food availability or predator abundance (ICES, 2003a,c), they disregard the impacts of long-term change in hydrographic conditions, such as shifts initiated by, for example, a weakening of the thermohaline circulation (THC), because the models are normally used for short-term predictions of the dynamics of fish stocks.

Studies of stock trajectory as a function of environmental conditions indicate that recruitment success of cod (*Gadus morhua*) increases with warmer average water temperatures (Nilssen *et al*., 1994; Ottersen *et al*., 1994) for a given spawning-stock biomass, whereas year classes tend to be smaller during colder years. A change in hydrographic conditions towards colder temperatures in the Barents Sea attributable to a weaker THC would therefore adversely affect recruitment success and thus the overall stock trajectories of Barents Sea cod. The capelin (*Mallotus villosus*) stock would be similarly affected by such a change in the Barents Sea temperature regime, because reduced food availability would negatively influence the growth of individual capelin as well as the overall stock size (Skjoldal *et al*., 1992). Such stock size reductions inevitably have an effect on the fisheries of both species.

This study uses a bioeconomic simulation model to assess the economic impacts that a sudden change in the fish population dynamics would have, focusing on the Barents Sea cod and capelin fisheries. The model covers a time period of a century and looks at the economic effects of changes in the population dynamics of fish stocks, namely the intrinsic rate of production and the environmental carrying capacity. Cod and capelin fisheries were selected because the cod fishery is of great economic importance in Norway, and capelin are one of the main food sources of cod. Therefore, changes in the Barents Sea capelin stock would have an effect on the cod stock as well. For the purpose of this analysis, the fisheries of cod and capelin in the Barents Sea are introduced and existing studies that apply bioeconomic models to the fisheries in the Barents Sea are reviewed. The model used for the analysis and the data applied are presented, and results of the simulations given. Later, we discuss the consequences that a severe change in fish population dynamics would have on the fisheries for Arcto-Norwegian cod and Barents Sea capelin.

4.3 Background

4.3.1 Cod and capelin fisheries in the Barents Sea

The Arcto-Norwegian cod stock, also referred to as the Northeast Arctic cod stock, is the most valuable fish stock in the Barents Sea. It is the most abundant of the Atlantic cod stocks, and is one of the most commercially important fish stocks worldwide (Sumaila, 1995). Arcto-Norwegian cod prey mainly on capelin, herring (*Clupea harengus*), haddock (*Melanogrammus aeglefinus*), young cod, shrimp (*Pandalus borealis*), and other invertebrates (Mehl, 1989).

In the past, the size of the Arcto-Norwegian cod stock has varied significantly. Overall, total biomass declined from more than 3 million tons in the 1950s to roughly a million tons in the 1980s, probably driven by increased fishing (ICES, 2003a). Short-term increases in the total biomass only occur when there has been particularly successful recruitment to the stock (Mehl & Sunnanå, 1991); such was the case when cod increased to >2 million tons in the early 1990s.

Annual catches of Arcto-Norwegian cod fluctuated between 400 000 and 1 200 000 t until the late 1970s (ICES, 2003a), then declined to roughly 400 000 t, coinciding with the reduction in stock size, before recovering at the beginning of the 1990s, when the stock again became abundant. At present, there are about 60 Norwegian trawlers and 640 small coastal vessels engaged in the fishery (Statistisk Sentralbyrå, 2002). Recent annual catches of Arcto-Norwegian cod amount to roughly 270 000 and 130 000 t from trawlers and coastal vessels, respectively.

The Barents Sea capelin stock is also of great importance, not only commercially, but because it is one of the main prey species of cod. Data on capelin show that between 1972 and 1984, the size of the stock was relatively stable at around 4 million tonnes (Gjøsæter *et al.*, 1998), before being reduced to <200 000 t in the mid-1980s and mid-1990s. Although there have been periods of quick recovery, they did not last long, because the sharp increases in capelin biomass, e.g. in the early 1990s, can be attributed to the recruitment success of just one or two year classes.

Annual catches of Barents Sea capelin amounted to more than a million tons during the stable period of the capelin stock size until the mid-1980s. The stock then collapsed within two years, forcing closure of the fishery until 1990 (Gjøsæter *et al.*, 2002). For the short period of stock recovery the fishery was re-opened, but catches were fairly low. Fishing activities ceased again from 1994 to 1998. The subsequent increase in stock size was rather short-lived, so harvesting of Barents Sea capelin was only possible for a few years. When the stock decreased recently the fishery was again closed, because the capelin harvesting strategy calls for the total allowable catch (TAC) to be set such that the probability of the spawning-stock biomass remaining above a threshold of 200 000 t is 95% (CEC, 2005). Because of the stock's great variability, a capelin TAC based on such a strategy needs to be set to zero quite often. Exploitation of cod and capelin stocks is managed jointly by Norway and Russia. The Joint Norwegian Russian Fisheries Commission splits TACs and divides the quotas among the countries. In 2004 and 2005, the TAC for Arcto-Norwegian cod was 486 000 and 485 000 t, respectively (Michalsen, 2004; CEC, 2005). However, owing to the poor current state of the capelin stock, both countries agreed to refrain from fishing capelin in 2004 and 2005.

4.3.2 Bioeconomic modeling of Barents Sea fisheries

Modeling studies of the Barents Sea fisheries have focused on both the biological and the economic consequences of different management strategies or different economic regimes. The single-species model CAPELIN was a first attempt to simulate the trajectories of capelin stock size (Tjelmeland, 1985), being used to determine the harvest that would lead to optimal further enhancement. However, any focus on a single fish species has the disadvantage that species interactions will be neglected. Therefore the model BIFROST (Gjøsæter *et al.*, 2002) was developed to assess the short-term trajectory of the capelin stock, focusing on management of capelin only without neglecting species interactions.

Aggregated versions of the multispecies models *ECONMULT* (Eide & Flaaten, 1993) and *MULTSPEC* (Bogstad *et al.*, 1997) were developed for management purposes: the models were *ECONSIMP* and *MULTSIMP* (Eide & Flaaten, 1994). Analyses with these models show that it is economically advantageous to catch both cod and capelin, instead of just harvesting the more valuable cod and leaving the capelin in the sea as additional food source for cod. Moxnes (1992) included uncertainty in his analyses for the Barents Sea, and showed that considering the uncertainty arising from random variations, measurement errors or uncertain parameters can have a pronounced impact on model results and, thus, also on management decisions.

Sumaila (1995) used a bioeconomic model of the Barents Sea cod fishery that considers different fleet types to determine the size of the fishing fleets necessary to exploit the cod stock optimally. Application of an expanded version of this model, including a predator-prey relationship between cod and capelin, showed that a joint strategy of harvesting both fish stocks leads to substantially higher profits from fishing than uncoordinated and competitive exploitation (Sumaila, 1997).

Eide (1997) and Armstrong & Sumaila (2000) analyzed the influence of cod cannibalism on the cod fisheries. Results showed that economically optimal use of the cod stock can only be achieved if the impact of cannibalism is acknowledged (Eide, 1997). According to these analyses, the present share of the cod trawlers should be reduced in favor of the smaller coastal vessels, because the latter generally target older cod than the trawlers (Armstrong & Sumaila, 2000), leading to improved economic results in the long term. Armstrong & Sumaila (2001) assessed the distribution of Barents Sea cod TAC among trawlers and coastal vessels and the implications of a possible introduction of individual transferable quotas (ITQs). They showed that ITQ introduction would not result in a significant improvement of the economic output owing to possible negative effects arising from one fleet type buying up all the quotas.

All studies listed above analyze aspects of the Barents Sea fisheries. However, environmental change is not addressed specifically in any of the models. Indeed, it is seldom addressed (Knowler, 2002). Changes in environmental conditions can affect fisheries population dynamics, which in turn have implications for economic output. This makes it necessary to account for changes in population dynamics when setting up a bioeconomic model that addresses long time horizons.

4.4 Methods

4.4.1 The simulation model

Generally, bioeconomic models are used to assess the magnitude of returns under different economic regimes, or to analyze optimal stock exploitation. Usually, the time horizon is only a few years and environmental conditions are considered to be constant.

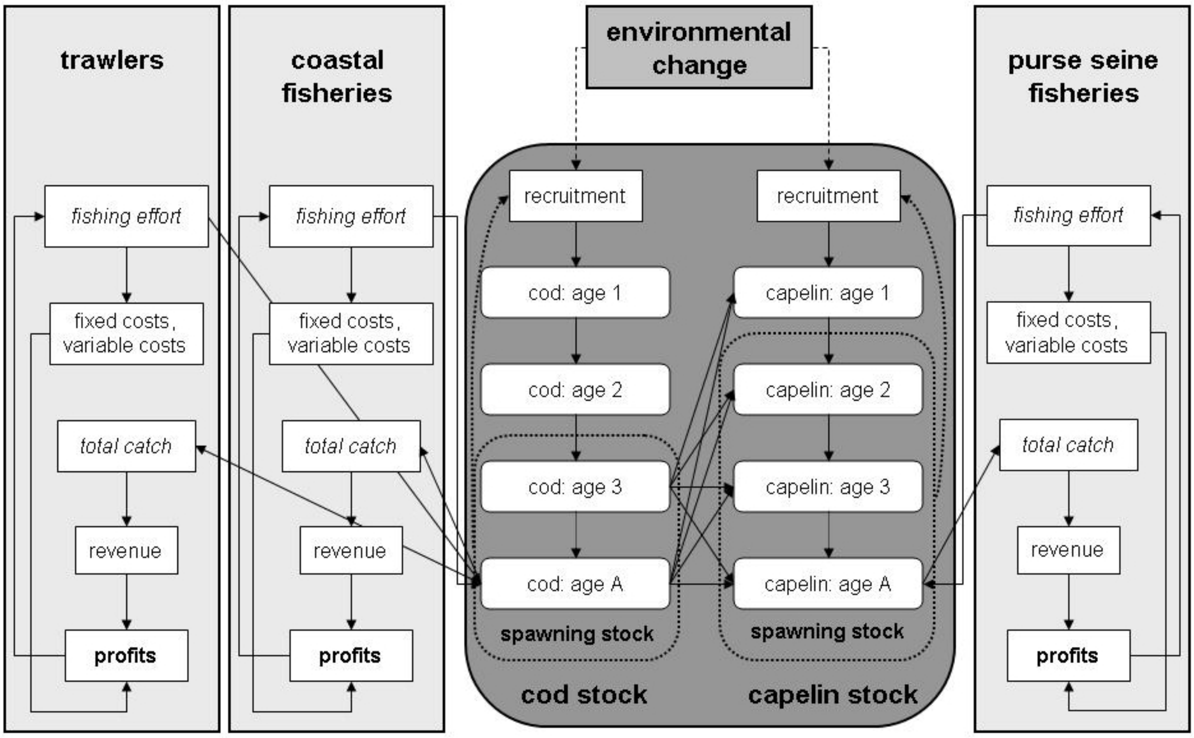

Figure 4-1: Structure of the simulation model

The model described here covers two important fish species of the Barents Sea that are harvested commercially, cod and capelin (Fig. 4-1). Cod prey on capelin. Two different fleet types are engaged in the cod fishery: large trawlers and smaller coastal vessels. Capelin are caught mainly by purse-seine; other means of catching capelin are of little importance and are therefore ignored for this analysis. 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. Management schemes, such as quotas, are disregarded.

The time horizon is one century, and each fishing period lasts one year. Changes in stock size in each fishing period are attributable mainly to harvesting, natural mortality, predation, and recruitment. During the simulation, a change in productivity and/or carrying capacity takes place, forcing a change in recruitment and, in the long-term, stock trajectories. Variables concerning the economic exploitation of the stocks and population dynamics are calculated for each fishing period. By comparison with a reference scenario in which the productivities and carrying capacities remain unchanged, the economic impacts of changes in stock dynamics are assessed. In addition, sensitivity analyses using the reference scenario are conducted to determine the influence of changes in key parameters on the simulation results. These quantities are the share of capelin devoted to human consumption, the discount rate, and the extent to which new information on stock trajectories is utilized in determining the harvesting strategies of the fleets.

4.4.2 Population dynamics of cod and capelin

Cod and capelin stocks are divided into age classes: 15 for cod and five for capelin. Key equations of the model are listed in Table 4-1. The number of individuals in each age class and the stock biomass at the beginning of a fishing period are known (Eq. 4-1). Stock size is reduced through harvesting by the various fishing fleets (Eq. 4-2). Stocks interact via predation (Eqs. 4-6 and 4-7) with the rate of cod weight increase depending on the extent of capelin consumption (Eq. 4-8; cf. Magnússon & Pálsson, 1991). Average capelin weight-at-age is assumed constant.

Recruitment depends on the stock size at the end of the harvesting period (Eq. 4-3). The number of recruits (Eq. 4-4) is obtained using a Beverton and Holt recruitment model (Beverton & Holt, 1954) in which the parameters are set such that the equilibrium biomass of unexploited stocks in the reference scenario would be 6 million tons for cod (Sumaila, 1997) and 10 million tons for capelin. 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 oldest ‘‘plus’’ age class (Eq. 4-5).

	population dynamics of the fish species		exploitation of the stocks
(4-1)	$B^{init}_{s,t} = \sum_a w_{s,a,t} n^{init}_{s,a,t}$	(4-9)	$h_{s,i,a,t} = q_{s,i,a} n^{init}_{s,a,t} v_{s,i} e_{s,i,t}$
(4-2)	$n^{harv}_{s,a,t} = n^{init}_{s,a,t} - \sum_i h_{s,i,a,t}$	(4-10)	$r_{i,t} = \sum_{s,a} P_{s,i} h_{s,i,a,t} w_{s,a,t}$
(4-3)	$SSB_{s,t} = \sum_a \mu_{s,a} sw_{s,a} n^{harv}_{s,a,t}$	(4-11)	$\psi_{i,t} = \varphi_i + e_{i,t}\theta_i$
(4-4)	$R_{s,t} = \frac{\alpha_{s,t} SSB_{s,t}}{1+\beta_{s,t} SSB_{s,t}}$	(4-12)	$\pi_{i,t} = r_{i,t} - v_i \psi_{i,t}$
(4-5)	$n^{init}_{s,1,t+1} = R_{s,t}$ $n^{init}_{s,a+1,t+1} = \chi_{s,a} n^{harv/pred}_{s,a,t}$ $n^{init}_{cod,A,t+1} = \chi_{cod,A} n^{harv}_{cod,A,t} + \chi_{cod,A-1} n^{harv}_{cod,A-1,t}$	(4-13)	$\Pi_i = \sum_{t=t_0}^{t_0+14} e^{-\delta(t-t_0)} \pi_{i,t}$
	predation and weight increase		adaptive harvesting strategies
(4-6)	$D_{cap,t} = \frac{D^{\max}_{cap}}{1+\left(D^{\max}_{cap}-1\right)\left(\frac{B^{harv}_{cap,t}}{B^{std}_{cap}}\right)^{-\gamma}}$	(4-14)	$G^{\exp}_{s,t}\left(B^{init}_{s,t}\right) = g^{\exp}_{s,t} B^{init}_{s,t}\left(1-\frac{B^{init}_{s,t}}{K_{s,t}}\right)$
(4-7)	$B^{pred}_{cap,t} = \kappa_1 D_{cap,t} B^{harv}_{cod,t}$	(4-15)	$\Theta_{s,i,t} = \frac{\psi_{s,i}}{q_{s,i} B^{init}_{s,t}}$
(4-8)	$w_{cod,a+1,t+1} = w_{cod,a,t} + \widehat{w}_{cod,a}\left(D_{cap,t}\kappa_2 + \left(1-\kappa_2\right)\right)$	(4-16)	$G'^{\exp}_{s,i,t} - \frac{\Theta'_{s,i,t} G^{\exp}_{s,i,t}}{P_{s,i} - \Theta_{s,i,t}} = \delta$
		(4-17)	$e_{s,i,t+1} = \frac{g^{\exp}_{s,t}}{q_{s,i} v_i}\left(1-\frac{B^*_{s,t}}{K_{s,t}}\right)$
		(4-18)	$\bar{g}_{s,t} = \frac{B^{init}_{s,t} - B^{init}_{s,t-1}}{B^{init}_{s,t-1}}$
		(4-19)	$g^{\exp}_{s,t+1} = \lambda_s \bar{g}_{s,t} + \left(1-\lambda_s\right) g^{\exp}_{s,t}$

Table 4-1: Summary of model equations. See Appendix 1 for symbols.

4.4.3 The fisheries

All fleets engage in harvesting during each fishing period (Eq. 4-9). It is assumed that the demand curve is elastic, i.e. the market price for both species remains constant regardless of the quantities landed. Some capelin is sold for human consumption at a higher price whereas most of the catch is used to produce fishmeal and fish oil; we use a weighted average that is slightly above the capelin price for industrial use.

Profits of each fleet (Eq. 4-12) reflect differences between revenues from sales of landings (Eq. 4-10) and the total cost of fleet operation, consisting of fixed costs for fleet maintenance that are independent of fleet utilization and variable costs directly related to the extent of fleet utilization (Eq. 4-11).

In this study, profits from fishing during three different time periods of 15 years (the average lifetime of a vessel) each are of special interest: the period 30-44 years (i.e. a period before the change in population dynamics), 50-64 years (i.e. the period revealing short-term impacts of the change in population dynamics), and 70-84 years (i.e. a period in which long-term impacts of changes in population dynamics become evident). Profits are discounted at rate d (Eq. 4-13). The control variable is the fishing effort. The boundary condition for the economic exploitation of fish stocks is the population dynamics of the two species.

4.4.4 The harvesting strategy

Each fleet’s fishing effort (Eq. 4-17) is adjusted after each fishing period according to returns from fishing in the previous fishing period. This is done by comparing actual catch with a previously calculated target value of an expected harvest that can be determined based on the relationship between the unit costs of harvesting (Eq. 4-15) and stock trajectories (Eq. 4-16); cf. Clark, 1990) assuming logistic growth (Eq. 4-14). If the amount of fish landed is less (more) than the target catch size, fleet utilization is increased (decreased) by 10% in the following fishing period.

The expected productivity of the fish stock, which is important in calculating the target value of catches, is also updated. This is done on the basis of the observed stock size trajectories (Eq. 4-18), which are used in a learning function (Eq. 4-19) to determine a weighted average of the actual and previously expected rates of productivity. This weighted average is then used as a basis for the same calculations in the next fishing period.

4.5 Results

A series of simulations was conducted to assess the consequences of changes in fish population dynamics on the fish stocks and the resulting economic impacts. All simulations covered a time period of 100 years. In each simulation, a sudden decrease in productivity or environmental carrying capacity was set to occur in year 50. The initial stock sizes were obtained using the average number of individuals in each age class during the time period 1983-2002 for cod (ICES, 2003a) and capelin (ICES, 2003c). An overview of the parameters used in the simulations is given in Appendix 2.

4.5.1 Reduction in productivity

A decline in the rates of cod and capelin reproduction-induced productivity leads to smaller stock sizes. The cod stock decreases by roughly one-third for a reduction in productivity of 50% (Fig. 4-2). The periodicity of the fluctuation in stock size, which is a consequence of the rule of updating fishing effort of the fleets, increases substantially at smaller total-stock biomass. The capelin stock trajectory follows the same general pattern. In the reference scenario, the overall capelin stock biomass fluctuates around an average value of approximately 2 million tons. Reducing the productivity by 50% decreases the average stock size to roughly 1.5 million tons. The impact of the change in capelin productivity on the stock size becomes evident earlier than does a reduction in cod stock size owing to the much shorter lifespan of capelin and the fact that the change in population dynamics takes place at a point in time when the periodic trend of an increasing capelin stock size is suddenly reversed.

Because of the reduced stock sizes, annual cod and capelin catches decline. Compared with the reference scenario, in which annual trawl catches of cod fluctuate around 160 000 t and annual coastal vessel catches total slightly less than 100 000 t (Tab. 4-2), catches decline notably even for small reductions in productivity. The short-term decline in annual catches is slightly less than 10% for a small change in productivity, but reaches almost 20% for both fleet types when productivity is reduced by a larger margin. Comparison with a later simulation time period reveals that the short-term reduction in average annual catches is only the beginning of a negative trend that leads to a long-term decline in catches by more than 76% in some scenarios.

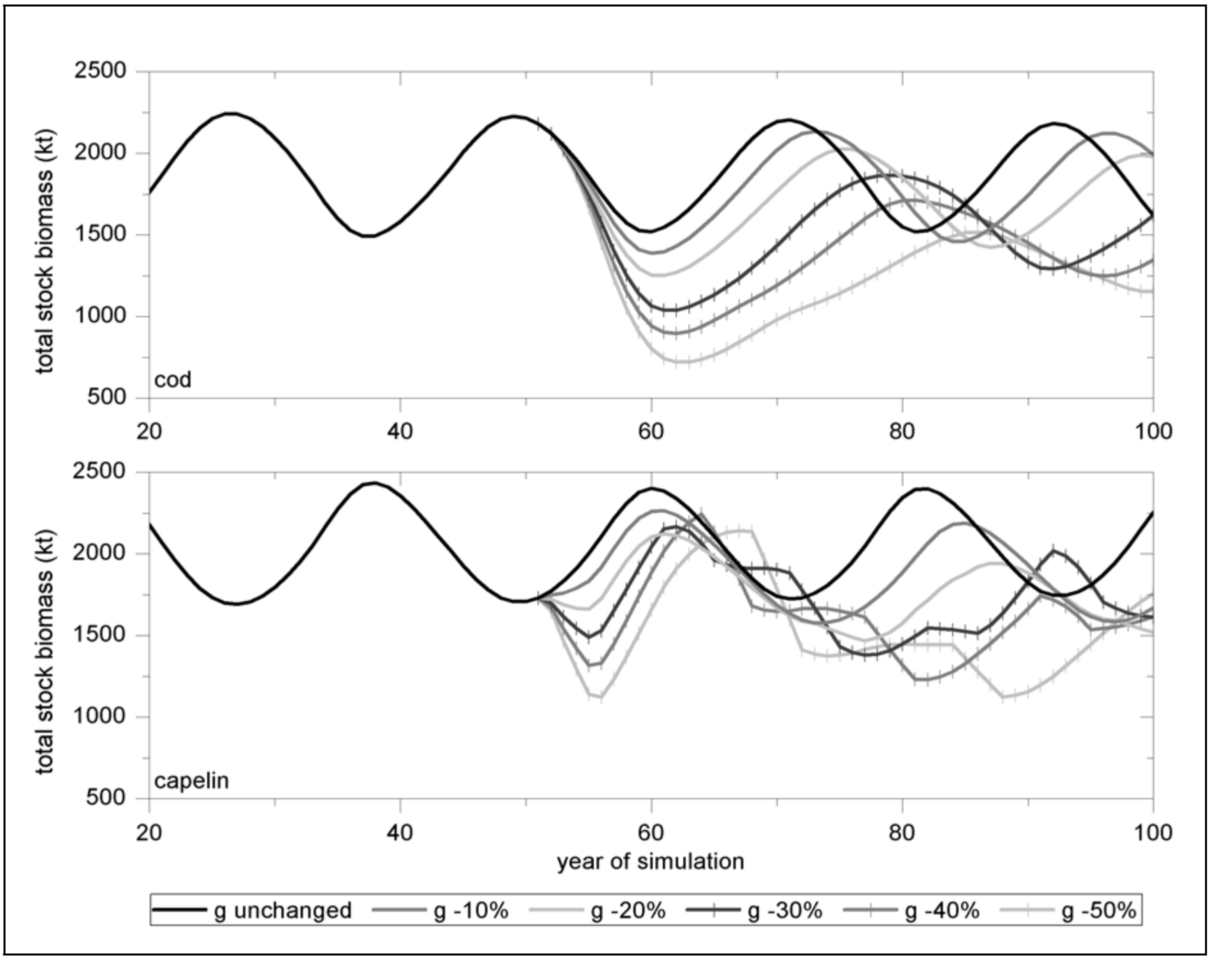

Figure 4-2: Stock size trajectories for cod and capelin with reduced productivity.

time period change of the rate of reproduction	**trawlers** (cod) average annual catch (1000 t)	 change from reference scenario	**coastal vessels** (cod) average annual catch (1000 t)	 change from reference scenario	**purse seiners** (capelin) average annual catch (1000 t)	 change from reference scenario
years 30-44	168.7		74.1		1022.3	
years 50-64						
reference scenario	164.7		98.1		977.5	
g -10%	157.1	-4.6%	94.6	-3.6%	938.9	-3.9%
g -20%	149.4	-9.3%	91.0	-7.2%	894.1	-8.5%
g -30%	150.6	-8.6%	85.2	-13.1%	842.3	-13.8%
g -40%	142.2	-13.7%	81.8	-16.6%	692.4	-29.2%
g -50%	132.4	-19.6%	81.8	-16.6%	637.3	-34.8%
years 70-84						
reference scenario	150.8		123.1		949.0	
g -10%	126.1	-16.4%	108.6	-11.8%	810.2	-14.6%
g -20%	93.4	-38.1%	85.2	-30.8%	682.7	-28.1%
g -30%	67.4	-55.3%	42.1	-65.8%	588.0	-38.0%
g -40%	40.0	-73.5%	28.4	-76.9%	524.1	-44.8%
g -50%	24.3	-83.9%	19.5	-84.2%	486.2	-48.8%

Table 4-2: Annual catch trajectories when productivity is reduced.

The market share of catches by trawlers and coastal vessels is also affected by the change in population dynamics. Trawl catches are initially more than twice those of coastal vessels. By the end of the simulation, the relative share of landings by coastal vessels increases in all scenarios. The extent to which the gap closes between the amounts caught by the two vessel types is particularly pronounced in the scenarios with large changes in population dynamics.

The overall trajectory of capelin catches is also negative (Tab. 4-2). However, the long-term impact is less extensive than for the cod catches, owing to the speedier adjustment of capelin to the new population dynamics, to reduced cod stock size, and the subsequent release of predation pressure.

time period change of the rate of reproduction	**trawlers** (cod) net present value of profits (million Nkr)	**coastal vessels** (cod) net present value of profits (million Nkr)	**purse seiners** (capelin) net present value of profits (million Nkr)
years 30-44	581.9	413.4	695.1
years 50-64			
Reference scenario	212.8	448.9	616.7
g -10%	211.4	448.4	614.8
g -20%	209.9	447.8	612.8
g -30%	208.6	447.1	610.7
g -40%	206.9	446.4	608.7
g -50%	205.0	445.7	606.8
years 70-84			
Reference scenario	-199.8	577.3	613.4
g -10%	-677.3	182.9	590.0
g -20%	-959.6	-115.2	586.8
g -30%	-998.4	-252.1	498.5
g -40%	-1107.3	-315.3	535.8
g -50%	-1198.4	-335.9	611.2

Table 4-3: Trajectories of net present value of profits when productivity is reduced.

The net present value of discounted profits in the period 50-64 years changes only very little despite considerable adjustments in stock sizes and landings caused by the changes in population dynamics (Tab. 4-3). As the large differences in economic returns from fishing only start about 5 years after the change in population dynamics, the significant economic consequences are partly hidden by discounting.

The long-term economic consequences of a reduction in productivity are more pronounced (Tab. 4-3). Cod fishing fleets suffer considerable reductions in profits. In all scenarios, the trawl fishery is hit hardest because of the high operational costs. Coastal vessel profits also become negative for large reductions in the productivity. In contrast, the capelin fishery is affected to a lesser extent. One reason is the less drastic decline in stock size caused by the change in population dynamics. Another reason is that the capelin stock and catches are higher around year 70 and lower at year 84, whereas the situation is opposite for cod as a consequence of discounting. The particularly bad years of the cod fishery are emphasized, while they receive less attention in the capelin fishery because they are near the end of the period of interest. However, the overall negative trajectories for all fisheries caused by reductions in productivity remain evident in all scenarios despite the influence of discounting.

4.5.2 Decrease in environmental carrying capacities

A reduction in the environmental carrying capacity of both fish species has an effect on the stocks similar to that of a reduction in the productivity. The cod stock, with an average stock size of roughly 2 million tons in the reference scenario, is heavily impacted. The initial decline in stock size after the reduction of the carrying capacity is particularly pronounced (Fig. 4-3). If the carrying capacity is reduced by 50%, cod biomass shrinks to less than 700 000 t. On the other hand, cod can recover in subsequent years in all scenarios. After such a slight recovery, cod biomass stabilizes at a level of more than 1 million tons. A decline in the carrying capacity leads to a longer periodicity of fluctuation of cod, which increases from 20 to almost 30 years between two peaks.

The impact of reduced carrying capacity on the capelin stock trajectory is less. With the stock biomass already fluctuating substantially in the reference scenario, only a reduction of the carrying capacity by 30% or more causes the stock size to clearly deviate downwards from the original range of fluctuation (Fig. 4-3). The reduction of the carrying capacity causes an initial decline of the stock, compared with the increase in the reference scenario. Subsequently, there is a rise in biomass that can be attributed mainly to the concurrent strong decline of the cod stock. This causes much smaller losses of capelin through predation by cod. A consequence of the reduced predation pressure is the marked increase in capelin stock biomass only a few years after the first breakdown of the population size.

Reduction in the environmental carrying capacity of cod severely affects the amount of cod harvested. In the long term, average annual landings by trawlers and coastal vessels both decrease by up to 75% (Tab. 4-4). However, the change in the carrying capacity leads to an increase in the harvest by trawlers during the first few years following the change of the carrying capacity. The greater the reduction in carrying capacity, the longer the time after year 50 in which the fishing effort by trawlers remains elevated. Consequently, average annual catches remain quite stable in all scenarios during the first decade after the change in carrying capacity, and are only slightly lower than in the reference scenario. On the other hand, the greater the effort to maintain large harvests, the more severe will be the long-term reduction in landings. Cod catches by both vessel types subsequently decline by up to 75% within only a few years, before stabilizing at a greatly reduced level, with total annual cod catches in some cases remaining below 100 000 t.

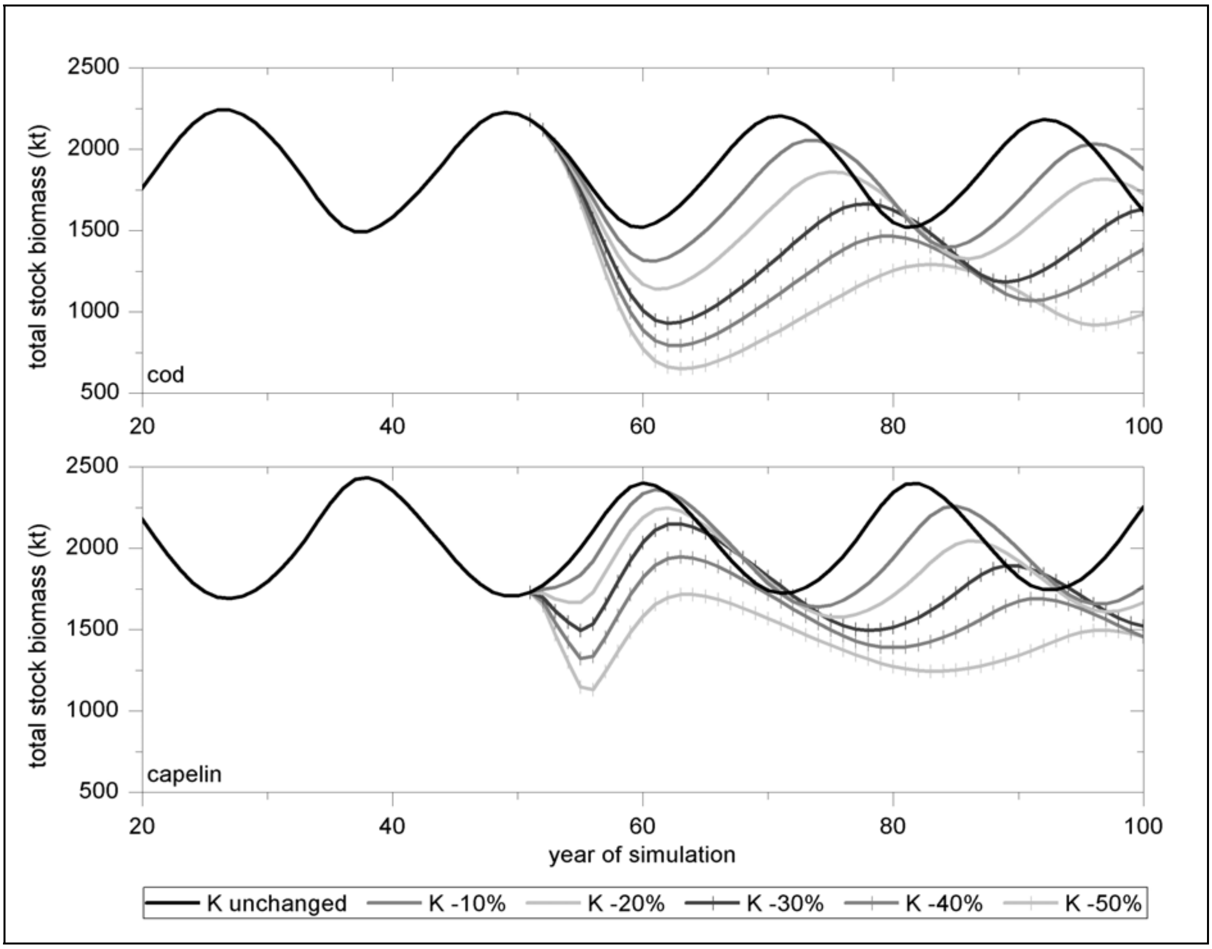

Figure 4-3: Stock size trajectories for cod and capelin with reduced carrying capacities.

In contrast, catches of capelin are less influenced by a change in the carrying capacity than by a reduction in productivity. For slight declines in carrying capacity, average capelin landings during the first decade remain practically unchanged (Tab. 4-4). Compared with the reference scenario, average annual harvests remain fairly stable in the long term, with average harvests still totaling more than 70% of the original value, even for a large reduction in carrying capacity.

time period change of the carrying capacity	**trawlers** (cod) average annual catch (1000 t)	change from reference scenario	**coastal vessels** (cod) average annual catch (1000 t)	change from reference scenario	**purse seiners** (capelin) average annual catch (1000 t)	change from reference scenario
years 30-44	168.7		74.1		1022.3	
years 50-64						
reference scenario	164.7		98.1		977.5	
K -10%	167.8	+1.9%	91.8	-6.4%	966.4	-1.1%
K -20%	157.8	-4.2%	93.6	-4.6%	928.1	-5.1%
K -30%	156.9	-4.7%	87.6	-10.7%	888.8	-9.1%
K -40%	147.2	-10.6%	83.9	-14.5%	821.7	-15.9%
K -50%	137.6	-16.5%	80.1	-18.3%	745.7	-23.7%
years 70-84						
reference scenario	150.8		123.1		949.0	
K -10%	148.6	-1.5%	84.9	-31.0%	848.3	-10.6%
K -20%	100.3	-33.5%	89.8	-27.1%	792.1	-16.5%
K -30%	84.3	-44.1%	50.9	-58.7%	753.8	-20.6%
K -40%	54.7	-63.7%	39.1	-68.2%	720.5	-24.1%
K -50%	32.6	-78.4%	22.4	-81.8%	679.5	-28.4%

Table 4-4: Annual catch trajectories when the environmental carrying capacity is reduced.

time period change of the carrying capacity	**trawlers** (cod) net present value of profits (million Nkr)	**coastal vessels** (cod) net present value of profits (million Nkr)	**purse seiners** (capelin) net present value of profits (million Nkr)
years 30-44	581.9	413.4	695.1
years 50-64			
reference scenario	212.8	448.9	616.7
K -10%	211.9	448.4	614.8
K -20%	210.3	447.9	612.8
K -30%	208.8	447.2	610.8
K -40%	207.0	446.5	608.8
K -50%	205.1	445.7	606.7
years 70-84			
reference scenario	-199.8	577.3	613.4
K -10%	-547.5	11.5	642.6
K -20%	-899.4	-84.9	684.2
K -30%	-962.9	-245.6	739.3
K -40%	-1079.3	-312.1	718.4
K -50%	-1189.6	-375.9	672.6

Table 4-5: Trajectories of net present value of profits when the environmental carrying capacity is reduced.

Reducing environmental carrying capacities has no negative short-term economic impact. The net present value of profits from fishing for all vessel types remains unchanged (Tab. 4-5). This is primarily because of the increased fishing effort on cod, keeping cod landings at high levels for up to four years longer than in the reference scenario. The depletion of the cod stock caused by this fishing behavior leads to significantly reduced predation on capelin. More capelin remains available for harvesting, which increases annual profits in the capelin fishery.

The long-term impacts of the change in environmental carrying capacity are bleak for the cod fishery (Tab. 4-5). Whereas coastal vessels remain profitable if the carrying capacity of cod is reduced only a little, the cod fishery is unprofitable for trawlers after a substantial decline in the carrying capacity. In the long term, the capelin fishery can even profit from a change in population dynamics: the net present value of profits is higher than in the reference scenario if cod reduction has occurred to allow less predation, leading to a larger capelin biomass and therefore larger harvests.

4.5.3 Combination of both effects

In this experiment, we explored the possibility that a change in environmental conditions causes both productivities and environmental carrying capacities to be affected at the same time, so changes in population dynamics were combined to assess how a simultaneous change of these quantities affects economic returns to the cod and capelin fisheries.

Results show that profits from fishing are only marginally affected when both changes in population dynamics occur concurrently. For a given change in the carrying capacities, a larger decrease in the productivity has only a small additional effect on the net present value of profits. Considering the period immediately following the change in population dynamics, discounted profits are similar for a given change in carrying capacity, regardless of the extent of the change in productivity. The impact of the increase in trawler effort to stabilize profits despite decreasing cod carrying capacity can be observed in all scenarios, regardless of the magnitude of an additional change in cod productivity. In the long term, however, a combination of reductions in productivity and carrying capacity of the two species causes the cod fisheries of both fleets to become unprofitable while profits of the purse-seine fishery for capelin remain positive for the remainder of the simulations.

4.5.4 The influence of the share of capelin devoted to human consumption

Traditionally, most Norwegian capelin catches are used to produce fishmeal and fish oil. In recent years, there has been an increase in the amount of capelin exported and used for human consumption. Some 50% of the capelin landed by Norway were exported in 1999 (Statistisk

Sentralbyrå, 2002), the market price being up to seven times as high as the price for capelin used industrially in Norway (Fiskeridirektoratet, 2001).

In a sensitivity analysis, the share of capelin used for human consumption was set to different levels between 0% and 50%, the market price of capelin being increased with more used for export. We assume that capelin market price used industrially $P_{cap,ind}$ is 0.60 Norwegian kroner (crowns; Nkr) per kg while the capelin market price used for consumption $P_{cap,hum}$ is Nkr 4.20 per kg, so the average price level of capelin in the simulations turns out to be between Nkr 0.60 and Nkr 2.40 per kg.

average market price of capelin (Nkr / kg)	*years 30-44* net present value of profits (million Nkr)	*years 50-64* net present value of profits (million Nkr)	*years 70-84* net present value of profits (million Nkr)
0.60	695.1	616.7	613.4
0.96	1180.5	1055.2	1049.9
1.32	1666.0	1493.7	1486.4
1.68	2151.4	1932.1	1922.9
2.04	2636.9	2370.6	2359.4
2.40	3122.3	2809.1	2795.9

Table 4-6: Trajectories of net present value of profits in the capelin fishery when the capelin average market price increases.

Simulations with different capelin price levels show that the quantity of capelin caught in each fishing period does not change despite the increased value of the resource. This is because in all scenarios, the catch by purse-seiners is so high as to leave little room for fishing effort to expand. However, the net present values of profits of the capelin fishery increase substantially (Tab. 4-6) for a higher average price of capelin during all time periods of the simulations. If an average of just 10% of the capelin is used for human consumption, the net present values of profits are almost doubled. By contrast, the cod fishery remains virtually unaffected by changes in the price of capelin, because landings and profits from fishing remain practically unchanged.

4.5.5 The influence of the discount rate

All simulations described have been conducted with a discount rate of 7%. In order to determine the influence of the discount rate on profits, simulations relative to the reference scenario are conducted with discount rates ranging from 1% to 15%. In this sensitivity analysis, there is no change in population dynamics, to ensure comparability between the scenarios. Net present values of profits are calculated for the three time periods of interest. Results indicate that the relationship between the net present value of profits and the interest rate is similar in all three periods, so the assessment of the time period between years 30 and 44 can be used as an example for all three periods of interest.

Results show that discount rates have a profound impact on the net present value of profits, which are affected differently depending on fleet type. Low discount rates lead to the worst overall net present value, which is negative because of losses made by both trawlers and coastal vessels (Tab. 4-7). High discount rates only favor the net present value of profits of capelin fishing fleets, whereas the economic results of cod fishing fleets diminish. Overall, the net present value of profits is greatest at moderate discount rates between 7% and 11%, when the economic results of all fishing fleets are distinctly positive.

discount rate	**trawlers** (cod) net present value of profits (million Nkr)	**coastal vessels** (cod) net present value of profits (million Nkr)	**purse seiners** (capelin) net present value of profits (million Nkr)
1 %	-816.5	-192.9	104.0
3 %	-376.3	152.9	282.7
5 %	208.7	298.6	511.1
7 %	581.9	413.4	695.1
9 %	711.2	413.9	833.4
11 %	593.1	458.6	1053.0
13 %	458.9	247.2	1246.3
15 %	-98.4	46.0	1397.8

Table 4-7: Influence of the discount rate on fishing profits.

In general, the trend is the same for both cod fleets. The scheme is different for the capelin purse-seine fleet. The size of the capelin stock and therefore the landings fluctuate more than the cod stock and cod catches. Consequently, the profitability of the capelin fishery tends to increase with higher discount rates, because good fishing years at the beginning of the period of interest are offset to a lesser degree by worse harvests just a few fishing periods later.

4.5.6 The influence of the learning factor

We examined the importance of the speed at which fishers adjust their harvest strategies. Even without changes in the population dynamics, the economic result of a fishing fleet changes depending on the speed at which fishers utilize new information about the trends in fish stock sizes.

A learning factor of 0.5 in the simulations leads to a solid overall economic result, with similar net present values of profits for all fleet types. However, considering the net present value of profits from fishing during years 50-64, which is representative of all three periods of interest, none of the fleets obtain the best economic result at such a speed of strategy adjustment. For purse-seiners, it is advantageous to utilize information on the population dynamics of the capelin stock as fast as possible (Tab. 4-8), even though differences between the returns from fishing vary little with learning factor.

learning factor	**trawlers** (cod) net present value of profits (million Nkr)	**coastal vessels** (cod) net present value of profits (million Nkr)	**purse seiners** (capelin) net present value of profits (million Nkr)
0.1	-414.5	62.1	725.0
0.2	-343.8	118.9	658.4
0.3	-86.7	670.5	619.3
0.4	-86.7	670.5	619.3
0.5	212.8	448.9	616.7
0.6	212.8	448.7	616.7
0.7	212.8	448.7	616.7
0.8	415.0	532.9	685.5
0.9	329.3	685.9	725.0

Table 4-8: Influence of the learning factor on fishing profits.

Relying only on the long-term trajectory of the cod stock leads to very bad economic results that might even include losses (Tab. 4-8). For cod fishers, it is best to utilize much of the newly gained information, i.e. to place greater weight on the real stock trajectory than on the previously applied expected stock growth rates when updating the expected productivity. The best economic result for trawlers is achieved with learning factors of 0.8 or 0.9. However, for coastal vessels, which target slightly older age classes than trawlers, the importance of previous experience of fishers is greater. Their best economic results are obtained for learning factors between 0.3 and 0.4.

4.6 Discussion and conclusions

Simulations reveal that adverse changes in fish population dynamics can have long-term negative impacts on the stock sizes of the fish species assessed. Reducing productivity or environmental carrying capacity leads to smaller stock sizes, which will cause landings to decrease. Results for the cod stock show that the decline in stock size is slightly greater when the carrying capacity is affected than when the productivity changes.

Capelin decline less than cod. The extent of the decline is about the same for both types of change in population dynamics. That the decline in capelin is not greater for a reduction in the carrying capacity can be attributed to the interaction between the two species in the simulation model. When the carrying capacities of the two species are reduced, the cod stock is significantly affected, causing a release in predation pressure. To a large part, this offsets the initial effect of changed carrying capacity on the capelin stock.

The reduced landings of both species negatively affect fisheries economics. However, the net present value of profits between years 50 and 64 veils the extent of the long-term impacts of changes in population dynamics. Discounting causes years with high catches at the beginning of a 15-year period to be more important than years with lower catches at the end of the same time period. Consequently, the net present value of profits of this time period remains unchanged.

Interestingly, an increase in fishing activity during the sixth decade of the simulation despite a reduced carrying capacity is hidden by the stable net present value of profits. The greater the change in population dynamics, the more the fishing effort is increased to maintain the high level of catches. Increased fleet utilization results in short-term economic gain, so returns remain at the same level as in the reference scenario. The strategy to increase fleet utilization to preserve large landings is rather short-sighted. Catch sizes and profits can be kept stable at a high level for just a few years longer with reduced stock size. However, this exploitation scheme causes such great harm to the cod stock that a recovery of the stock in later years is practically impossible.

The long-term negative trend in catch size caused by changes in population dynamics and the subsequent diminishing economic returns is clearly evident. The net present value of profits during years 70 through 84 shows that the more valuable cod fishery is more affected by negative stock size trajectories than the capelin fishery. The cost-intensive operation of large trawlers requires that annual landings do not drop considerably below current levels. In many scenarios, the cod trawler fishery becomes unprofitable if stock sizes decline such that the initial harvests can no longer be sustained.

A comparison of the simulation results with ICES stock assessment data shows that the average stock size of cod in the model and the calculated trawler and coastal vessel catches prior to the change in population dynamics agree relatively well with the official statistics. Currently, the cod stock in the Barents Sea has a biomass (age 3 and older) of about 1.5 million tons and cod landings total roughly 450 000 t, most of which is caught by trawlers (ICES, 2003a; Michalsen, 2004). In the simulations, the cod stock biomass averages about 1.9 million tons in the reference scenario and annual harvests amount to around 250 000 t. In contrast, there are larger discrepancies between model results and observed values for the capelin stock and the quantity of capelin harvested. The model generally overestimates capelin stock size, which causes the purse-seine catch of capelin and the subsequent economic result for this fishery to be too high. A possible reason for this discrepancy between model and reality is that the model only considers the predator-prey relationship between cod and capelin, neglecting interactions of capelin with other species in the ecosystem.

It is possible that the quality of simulation results of capelin stock size can be improved if herring is considered as a third species in the model. Young herring feed extensively on capelin larvae. If large year classes of young herring are present in the Barents Sea, their predation on capelin larvae can severely impact capelin recruitment success (Gjøsæter & Bogstad, 1998). The consequence would be a significantly reduced capelin stock that can only rebuild when the young herring have left the Barents Sea to join the adult herring stock in the Norwegian Sea. Even though large year classes of young herring are found in the Barents Sea infrequently, their predation leads to a smaller adult stock of capelin and increased variability in the capelin biomass in subsequent years.

Another difficult aspect of the model set-up is to represent the harvest strategies of the fishers in a realistic manner. In this model version, the harvest strategies are not based on rational behavior that only considers maximization of profits over a certain time period as the sole basis of decision-making, but on adaptation. Adaptation of harvest strategies is characterized by the adjustment of fleet utilization based on a comparison of the catch size with a previously calculated target value. As the criteria for adjusting fishing effort do not depend on the profit from fishing in the fishing period in question, but rather on the proximity to the target value, the profits from fishing obtained by following this strategy are obviously smaller than profits that would have been obtained if profit-maximizing harvesting strategies had been addressed.

Adaptive harvesting strategies were used in this model because they have the advantage that the size of the fish stock and the expected recruitment success are considered when fishing effort is determined. Logistic stock growth functions were used in the calculation of target catch sizes instead of the data on the age structure and recruitment to the stocks from the biological module of this model. This way the calculations can be readily carried out, relying only on a limited number of key parameters underlying stock size trajectories. As the determination of harvesting strategies and the calculations involving the population dynamics of the two species are conducted independently, no problems arise from the use of two different underlying biological models in the two contexts. This set-up actually allows the assessment of different harvesting strategies of varying complexity without changing the update rules used to describe the stock trajectories.

In the long term, adaptive harvesting strategies seem more sustainable than profit-maximizing strategies, despite the fact that profits from fishing never reach the maximum possible value. However, simulation results with a reduced environmental carrying capacity of cod show that even adaptive harvesting strategies can be detrimental to a stock size trajectory. This holds particularly in cases in which restrictions to the adaptation rule cause the adjustment of fishing effort to be too slow to ensure sustainable management of the fish stock.

Despite these caveats, it is possible to use this simulation model to obtain some preliminary insights into the possible consequences of a reducing productivity and/or environmental carrying capacity on cod and capelin stocks in the Barents Sea and the catches of their fisheries. The model will now be further developed in order to obtain a more differentiated image of the economic consequences caused by a sudden change of the population dynamics of the exploited fish stocks. This will enable us to analyze particular scenarios that arise from changes in climatic or hydrographic conditions.

4.7 Appendix 1: List of symbols used in the model

symbol	**meaning**
a	index denoting the age class
A	highest age class of a species
B	Biomass
cap	index referring to capelin
cod	index referring to cod
D	prey density
e	fleet utilization
g	rate of reproduction
G	expected growth of the stock
h	Harvest
harv	index denoting the stock size after harvesting has been considered
hum	index referring to human consumption
i	index denoting the fleet type
ind	index referring to industrial use
init	index referring to the beginning of a fishing period
K	carrying capacity
n	number of individuals in an age class
P	fish price
pred	index denoting the stock size after harvesting and predation have been considered
q	catchability coefficient
r	Revenue
R	recruitment
s	index denoting the species
SSB	spawning stock biomass
sw	spawning weight
t	index denoting the fishing period
v	number of vessels
w	Weight
α	parameter used in recruitment function
β	parameter used in recruitment function
δ	discount factor
θ	variable costs
Θ	cost per unit effort
$\kappa1$	rate of predation
$\kappa2$	parameter used in calculation of predated biomass
λ	learning factor
μ	share of mature individuals
π	profit per fishing period
Π	net present value of profits over a 15-year period
φ	fixed costs
χ	natural survival rate
ψ	total costs

4.8 Appendix 2: 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 (2003c)
mean weight in each age group $w_{cap,a}$	[0.0036 0.0102 0.0182 0.024 0.0265] kg	based on ICES (2003c)
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 $sw_{cap,a}$	[0.00324 0.00918 0.01638 0.0216 0.02385] kg	calculated from mean weight-at-age
natural rate of survival χ_{cap}	0.535	Eide & Flaaten (1994)
initial value rate of reproduction $g_{cap,0}$	0.5	
initial value carrying capacity $K_{cap,0}$	10 million t	
initial value recruitment parameter $\alpha_{cap,0}$	4491	set to be consistent with initial carrying capacity
initial value recruitment parameter $\beta_{cap,0}$	9	set to be consistent with initial carrying capacity
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)
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)
mean spawning weight per age class $sw_{cod,a,0}$	[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
natural rate of survival χ_{cod}	0.8	Sumaila (1995)
initial value rate of reproduction $g_{cod,0}$	0.5	Eide (1997)
initial value carrying capacity $K_{cod,0}$	6 million t	Sumaila (1995)
initial value recruitment parameter $\alpha_{cod,0}$	682	set to be consistent with initial carrying capacity
initial value recruitment parameter $\beta_{cod,0}$	1.5	set to be consistent with initial carrying capacity
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	1.235	Moxnes (1992)
influence of predation on weight of cod κ_2	0.6	Moxnes (1992)

economic parameters of trawlers		
fleet size v_{TR}	60	adapted from Statistisk Sentralbyrå (2002)
catchability coefficient q_{TR}	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		
fleet size v_{CV}	500	adapted from Statistisk Sentralbyrå (2002)
catchability coefficient q_{CV}	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		
fleet size v_{RW}	70	adapted from Statistisk Sentralbyrå (2002)
catchability coefficient q_{RW}	0.0175	adapted from Sumaila (1997)
fixed costs φ_{RW}	0.42 million Nkr	adapted from Sumaila (1997)
variable costs θ_{RW}	0.58 million Nkr	adapted from Sumaila (1997)
general economic parameters		
discount factor δ	0.07	Sumaila (1995)
market price of capelin that is used industrially $P_{cap,ind}$	Nkr 0.60 / kg	based on Fiskeri-direktoratet (2001)
market price of capelin that is used for consumption $P_{cap,hum}$	Nkr 4.20 / kg	based on Fiskeri-direktoratet (2001)
market price of cod P_{cod}	Nkr 6.78 / kg	Sumaila (1995)
learning factor λ_s	0.5 for all fleets	

5 Economic impacts of changes in fish population dynamics: the role of the fishermen’s harvesting strategies

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This chapter has been submitted for publication.

5.1 Abstract

Using a bioeconomic model of the cod (*Gadus morhua*) and capelin (*Mallotus villosus*) fisheries of the Barents Sea, this study assesses the role of the fishermen’s behavior in reducing or intensifying the effects on the stocks caused by altered population dynamics. The analysis focuses on the economic development of the fisheries employing a profit-maximizing harvesting strategy over a given number of fishing periods. The scenarios assessed cover a time period of 100 years with sudden changes of the productivity of both species occurring at the midpoint of each simulation. Stock sizes and landings of fish are determined for each fishing period, and the net present values of profits over periods of interest prior to and following the change in population dynamics are calculated. Results show that if the profit-maximizing harvesting strategy is based on a short optimization period, the fleets with the higher efficiency are generally favored. If the strategy is based on an optimization over two or more fishing periods, fishing activities may be deferred to allow for stock regrowth. In such cases, smaller and less cost-intensive vessels are preferred. A reduction of either the productivity or the carrying capacities of the two species has little impact on the fisheries if the change is fairly small. A substantial reduction of either quantity has a lasting negative economic impact which mainly manifests itself in a severely reduced profitability of mainly the cod fishery.

5.2 Introduction

Changes in the population dynamics of fish can be brought about by altered environmental conditions. Shifts in temperature, salinity, or oxygen content have a direct influence on the reproductive success of fish species. A change in hydrographic conditions towards colder temperatures in the Barents Sea, e.g. due to a weaker thermohaline circulation (THC), would adversely affect recruitment success and thus the overall development of the Arcto-Norwegian cod (*Gadus morhua*), since recruitment success of cod increases with warmer average water temperatures (Nilssen *et al*., 1994; Ottersen *et al*., 1994) for a given spawning stock biomass whereas year classes tend to be smaller during colder years. Capelin (*Mallotus villosus*) would be similarly affected by such a change in the Barents Sea temperature regime due to reduced food availability (Skjoldal *et al*., 1992).

Lower productivity leads to smaller standing stock sizes and can sometimes even cause complete stock collapses, especially if the stocks are commercially exploited. For example, in the 1980s, the Barents Sea capelin stock collapsed after a shift in temperature which led to unfavorable recruitment conditions (Jennings & Kaiser, 1998). Johnston & Sutinen (1996) show that the risk of a stock collapse due to environmental change increases the speed of optimal exploitation of the stock, regardless whether or not fishermen could turn to a replacement species if necessary. An aggressive harvesting strategy can therefore accelerate the depletion of a stock if it is employed in times of poor recruitment success. On the other hand, the use of a fishing strategy that allows deferring catches, such as profit-maximization over more than one fishing period under perfect market conditions, can help prevent or postpone the demise of a population by maintaining a larger spawning stock and thus improving chances of recruitment success.

The choice of an appropriate harvesting strategy by individual fishermen ultimately determines the success of large-scale management strategies. In an analysis of long-term fishing policies, Lane (1988) shows that there is often competition among fishermen striving to maximize their benefits. Short-term considerations of fishermen often focus on the improvement of their individual position within the fishing fleet, while in the long run the preservation of the stock plays a more important role. The objective of profit maximization as prime goal of the fishermen is generally more applicable in industrial than in small-scale fisheries (Robinson & Pascoe, 1997). It may be the key motivation for effort allocation in many fleets, but there are other factors influencing the fishermen's behavior. An unstable and highly variable development of a fish stock can cause fishermen to refrain from the objective of profit maximization and to turn to cost-covering instead, just in order to remain in the market even through periods of low returns from fishing (Chaboud, 1995). Salas & Gaertner

(2004) stress the importance of incorporating the adaptation of the behavior of the fishermen to changes in fish population dynamics in fisheries models in addition to the ecosystematic interactions between the species incorporated in the model.

Depending on the strategy chosen, anthropogenic harvesting regimes can intensify or alleviate the consequences of the environmental change for the population dynamics. In the previous chapter of this thesis, we assessed the impacts of changes in population dynamics of the Barents Sea fish stocks if the fishermen follow adaptive harvesting strategies, i.e. the fishermen determine the extent of the fishing effort based on the economic result of the previous fishing periods. This study analyzes the economic development in situations of reduced reproductive success of the Barents Sea cod and capelin stocks for rational expectations of the fishermen, i.e. effort levels are determined solely on the basis of reaching the maximum possible economic returns from fishing over a specified number of fishing periods within the limits of fisheries management advice. This corresponds to the current management scheme of the Barents Sea fisheries: there is a total allowable catch (TAC) for both species but within this limit the fleets compete for the resources.

The bioeconomic simulation model focuses on the fisheries of the interacting stocks of Arcto-Norwegian cod and capelin in the Barents Sea. It covers a time period of a century and looks at changes in productivity and the environmental carrying capacities. Cod and capelin fisheries were selected because of the great economic importance of the cod fishery and the important predator-prey relationship between the species. Therefore, changes in the Barents Sea capelin stock size will have an effect on the cod stock as well. In the following, the fisheries of cod and capelin in the Barents Sea are introduced. Then the effects of changes in the intrinsic growth rate or the carrying capacity on the equilibrium stock size are discussed for a simple bioeconomic model. The model used here and the data applied are presented in the subsequent section. Results of our model simulations are given in sections three and four. Section five discusses the consequences of changes in fish population dynamics on profit-maximizing fisheries of the Arcto-Norwegian cod and Barents Sea capelin stocks.

5.2.1 The cod and capelin fisheries in the Barents Sea

The Arcto-Norwegian cod stock is one of the most important commercially exploited fish stocks in the world (Sumaila, 1995) and undoubtedly the most valuable stock in the Barents Sea. It is jointly managed by fleets from Norway and Russia who annually set the TAC which is divided almost equally among them (Hannesson, 1996). In recent decades the stock biomass has shown considerable variability, owing not only to the economic exploitation but also to changes in environmental conditions in the Barents Sea that are driven by the NAO (Hjermann *et al*., 2004b).

Long-term increases in fishing activity have led to a decline in stock size from more than 3 million tons in the 1950s to about 1 million tons in the 1980s (ICES, 2003a). Short-term increases since then can be attributed to particularly successful recruitment events (Mehl & Sunnanå, 1991). Cod is caught by large trawlers and numerous smaller coastal vessels. Annual catches of cod totaled slightly more than 400 000 tons in 2002 (ICES, 2003a). The current total allowable catch of Arcto-Norwegian cod is set at 485 000 tons (CEC, 2005).

The capelin stock shows even larger fluctuations in stock size owing to its short life-span and the considerable predation pressure by cod. The stock size was relatively stable in the 1970s at roughly 4 million tons before being reduced to less than 200 000 tons in the 1980s and mid-1990s (Gjøsæter *et al.*, 1998). Significant increases in stock biomass, as observed in the early 1990s are caused by the recruitment success of only one or two age classes and did not have a lasting impact. Annual catches rose steadily from the 1960s until the mid-1980s always exceeding 1 million tons, but dropped sharply over the course of only a few years, so that the capelin fishery needed to be closed from 1987 to 1990 (ICES, 2003c). Capelin was caught again for a few years in the early 1990s but fishing activities were halted again after a few years when the next dramatic decline of the stock occurred. At present, the fishery of Barents Sea capelin remains closed because of the consistently low stock biomass in recent years (CEC, 2005).

5.2.2 Effects of changes in population dynamics in a simple bioeconomic model

In the following, the exploitation of a single fish stock is assessed under varying environmental conditions for different economic regimes. The biological growth process is described by a logistic growth function (Schaefer, 1957). It relates the growth of the fish stock to its actual size B. In steady state, the amount of fish harvested h over a certain period of time equals the net biological growth of the fish stock. Thus h is proportionally related to the stock size by the fishing effort and the catchability coefficient q of the species.

In steady state, fishing revenue $r(B)$ relates to the size of the fish stock as

(5-1) $$r\left(B\right)=Ph=Pg_1B\left(1-\frac{B}{K}\right)$$

where g_1 refers to the productivity and K denotes the carrying capacity.

The total costs of harvesting the fish stock ψ are assumed to depend linearly on the fishing effort E, where ω is the cost per unit effort.

(5-2) $$\psi=\omega E=\frac{\omega g_1}{q}\left(1-\frac{B}{K}\right)$$

In an open access regime, profits are zero, which means that the total costs equal the total revenue for each economic actor in the market. New economic actors cannot be excluded from entering the market. This can be used to determine the equilibrium stock size B_{eq} under open access conditions OA:

(5-3) $$B_{eq,OA}=\frac{\omega}{Pq}$$

Changes in the biological behavior of the fish stock lead to changes in the open access equilibrium. If the cost function remains unchanged and the revenue function adapts to a changed productivity of the fish stock g_2, then the new equilibrium open access stock size becomes

(5-4) $$B^{*}_{eq,OA} = \frac{\omega g_1}{Pqg_2} = B_{eq}\frac{g_1}{g_2}$$

Figure 5-1 shows such a shift in the equilibrium stock size for open access fisheries. For instance, a reduction of the productivity of the fish stock by 25% ($g_2 = 0.75\ g_1$) would cause the equilibrium stock size to increase by a third.

The opposite effect occurs when the carrying capacity changes due to variations in the environmental conditions. Let $B_{max,1}$ be the initial carrying capacity and $B_{max,2}$ the carrying capacity after the change. Under the assumption that the cost structure remains unchanged and that the revenue curve adjusts to the new carrying capacity, the new equilibrium stock size of fish becomes

(5-5) $$B^{**}_{eq,OA} = \frac{\omega K_2}{PqK_1} = B_{eq}\frac{K_2}{K_1}$$

which is lower than the original equilibrium stock size prior to the reduction of the carrying capacity. Figure 5-1 shows a reduction of the carrying capacity by one third.

The consequences of economic exploitation of a fish stock are different if the fish is not harvested under open access but under perfect market conditions *PM*, e.g. if there is socially optimal exploitation of the resource and the social net benefits are maximized. In this case, the equilibrium stock size is

(5-6) $$B_{eq,PM} = \frac{\omega}{2Pq} + \frac{K}{2}\left(1 - \frac{d}{g_1}\right)$$

If the growth rate of the fish stock changes, the equilibrium stock size is

(5-7) $$B^*_{eq,PM} = \frac{\omega g_1}{2Pqg_2} + \frac{K}{2}\left(1 - \frac{d}{g_2}\right)$$

Thus, a lower growth rate increases the equilibrium stock size under open access (Fig. 5-1). With perfect market conditions, the equilibrium stock size may increase or decrease depending on the extent of the growth rate reduction, since the first term tends to increase with a lower growth rate while the second term decreases for a reduced *g*. For sufficiently large changes in the growth rate, the latter will dominate and lead to an overall decrease in the equilibrium stock size, as shown in the given example.

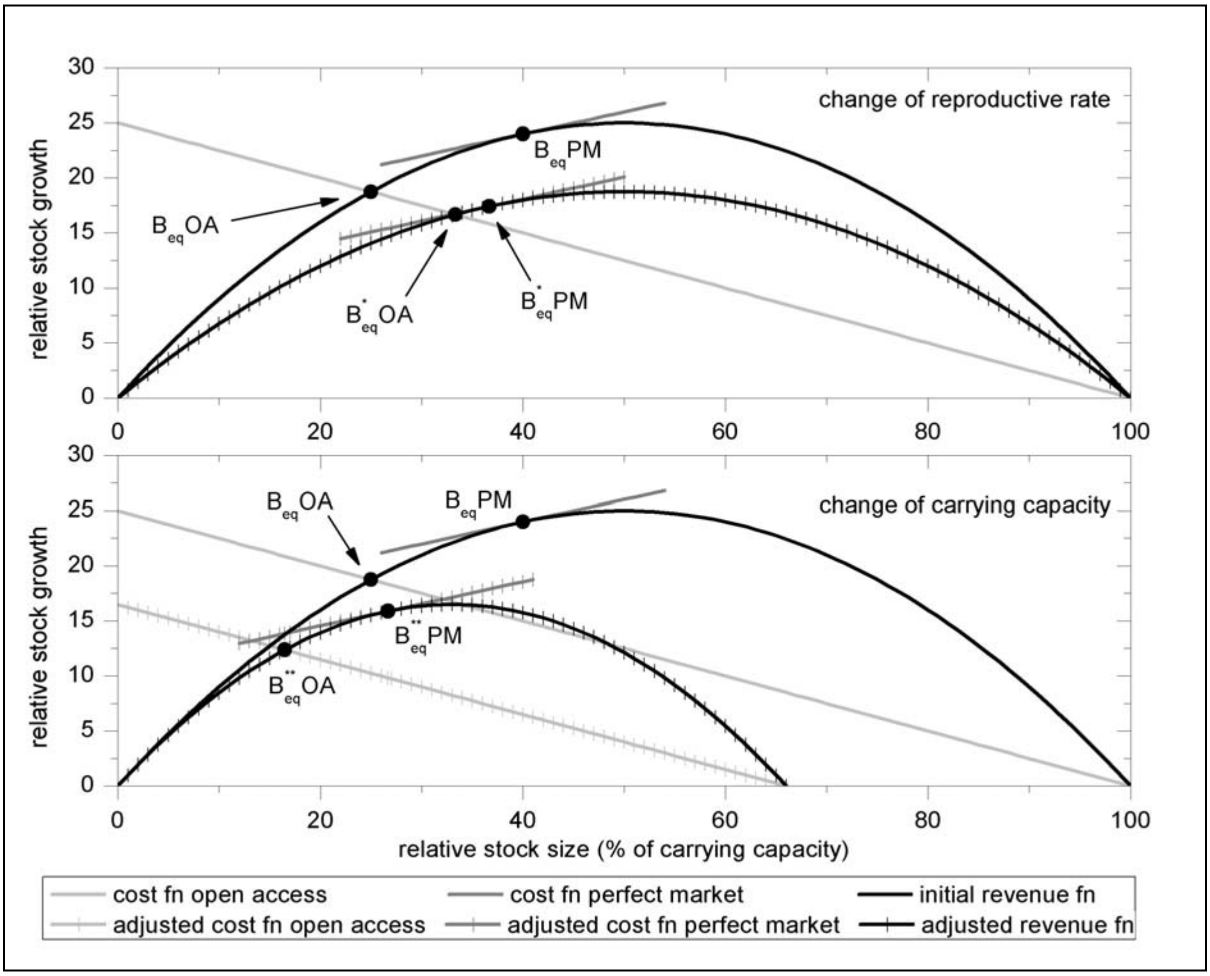

Figure 5-1: Impacts of a change of productivity or the carrying capacity in a simple bioeconomic model.

If the carrying capacity of the fish stock changes, the new equilibrium stock size under perfect market harvesting conditions is lower than the original equilibrium. Here the change occurs in the same direction as in the open access fishery where a decrease in the carrying capacity leads to a decline in the equilibrium stock size as well:

(5-8) $$B_{eq,PM}^{**} = \frac{\omega K_2}{2PqK_1} + \frac{K_2}{2}\left(1 - \frac{d}{g_1}\right)$$

The new steady state equilibrium stock size is significantly lower than the initial equilibrium stock size (Fig. 5-1).

This shows that a reduction in the carrying capacity has a more pronounced impact on the equilibrium stock size of the fish stock than a change in the growth rate of the fish. A reduction in the growth rate only leads to a slight decline in the equilibrium stock size under perfect market conditions while the equilibrium stock size even increases under open access conditions. On the other hand, a decline in the carrying capacity will have a severe negative impact on the equilibrium stock size under both harvesting regimes.

5.3 The model

In general, bioeconomic models of fisheries assess the magnitude of returns from fishing in a variety of scenarios with different economic conditions. Environmental conditions are usually considered to be constant, a reasonable assumption if the simulation period covers only a few years or decades. The model used in this study covers a longer time period. Changes in environmental conditions are assumed to influence the development of the stocks by affecting productivity or the environmental carrying capacities of the species. It is assumed that at the midpoint of each simulation, a sudden change of the productivity of both species and/or a reduction of the species' carrying capacities occurs which remains in effect until the end of the simulation period. Such shifts may occur if there are large-scale changes in hydrographic conditions, e.g. after a shutdown or considerable weakening of the THC, which would occur over a time horizon of only a few years. Therefore, the impact on the reproductive success of the fish stocks would be quite immediate as is the case in these simulations. Since a shift in the state of the THC would take a long time to reverse, we assume that the fish population dynamics remain in the altered state until the end of the simulation period.

Two species are covered in the model: cod and capelin. Cod prey on capelin. The cod stock is exploited by two competing vessel types, trawlers and coastal vessels. Since the purse seine fishery is the dominating form of capelin fishery, only this vessel type is considered here. Both stocks are jointly managed by Norway and Russia, but we do not distinguish between fishermen.

The simulations of the model extend over a time horizon of one century. A fishing period is one year. For reasons of comparability of the scenarios, inter-annual natural variability of recruitment success and survival rates of the individual age classes are disregarded. Variables concerning the development of the stock size and the economic exploitation of the two species are determined for each fishing period. The scenarios are compared to a reference case in which the population dynamics remain unaltered. In addition, sensitivity analyses using the reference scenario are conducted to determine the influence of changes in key parameters on the simulation results. These quantities are the share of capelin devoted to human consumption and the discount rate. Key equations of the model are listed in Table 5-1.

population dynamics of the fish species		exploitation of the stocks	
(5-9)	$B_{s,t}^{init}=\sum_{a} w_{s,a,t}n_{s,a,t}^{init}$	(5-17)	$h_{s,i,a,t}=q_{s,i,a}n_{s,a,t}^{init}v_{i,t}e_{s,i,t}$
(5-10)	$n_{s,a,t}^{harv}=n_{s,a,t}^{init}-\sum_{i} h_{s,i,a,t}$	(5-18)	$r_{i,t}=\sum_{s,a}P_{s,i}h_{s,i,a,t}w_{s,a,t}$
(5-11)	$SSB_{s,t}=\sum_{a}\mu_{s,a}sw_{s,a}n_{s,a,t}^{harv}$	(5-19)	$\psi_{i,t}=\varphi_i+e_{i,t}\theta_i$
(5-12)	$R_{s,t}=\dfrac{\alpha_{s,t}SSB_{s,t}}{1+\beta_{s,t}SSB_{s,t}}$	(5-20)	$\pi_{i,t}=r_{i,t}-v_{i,t}\psi_{i,t}$
(5-13)	$n_{s,1,t+1}^{init}=R_{s,t}$ $n_{s,a+1,t+1}^{init}=\chi_{s,a}n_{s,a,t}^{harv/pred}$ $n_{cod,A,t+1}^{init}=\chi_{cod,A}n_{cod,A,t}^{harv}+\chi_{cod,A-1}n_{cod,A-1,t}^{harv}$	(5-21)	$\Pi_i=\sum_{t=t_0}^{t_0+14}e^{-\delta(t-t_0)}\pi_{i,t}$
		(5-22)	$v_{i,t}=f\left(v_{i,t-1},\pi_{i,t-1\to t-5}\right)$
predation and weight increase			
(5-14)	$D_{cap,t}=\dfrac{D_{cap}^{\max}}{1+\left(D_{cap}^{\max}-1\right)\left(\dfrac{B_{cap,t}^{harv}}{B_{cap}^{std}}\right)^{-\gamma}}$		
(5-15)	$B_{cap,t}^{pred}=\kappa_1 D_{cap,t}B_{cod,t}^{harv}$		
(5-16)	$w_{cod,a+1,t+1}=w_{cod,a,t}+\widehat{w}_{cod,a}\left(D_{cap,t}\kappa_2+\left(1-\kappa_2\right)\right)$		

Table 5-1: Summary of model equations. See Appendix 1 for symbols.

5.3.1 Population dynamics of cod and capelin

The model distinguishes 15 age-classes 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 (Eq. 5-9). The number of fish is reduced by harvesting (Eq. 5-10). The predator-prey relationship between the two species is also considered by further reducing the number of capelin (Eqs. 5-14 & 5-15) and increasing weight of cod (Eq. 5-16, cf. Magnússon & Pálsson, 1991). The average capelin weight-at-age is assumed constant.

Recruitment adds to the lowest age class and depends on the stock size at the end of the harvesting period (Eq. 5-11). The number of recruits (Eq. 5-12) is determined by using a Beverton-Holt recruitment equation (Beverton & Holt, 1954), which is commonly used in age-structured models of the Barents Sea fish stocks. The parameters are set such that in the reference scenario the carrying capacities are 6 million tons for cod (Sumaila, 1997) and 10 million tons for capelin. They are updated after each fishing period based on a procedure by Clark (1990) that relates these parameters to the carrying capacity and reproductive potential. Thus, changes in fundamental stock properties are linked to recruitment success and therefore to the development of the stock over time. 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 (Eq. 5-13).

5.3.2 The fisheries

The number of fish caught (Eq. 5-17) is used to determine the weight of the entire catch in each fishing period. It is assumed that the demand curve is perfectly elastic, i.e. the market prices for both species remain constant regardless of the quantities landed. 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, we use a weighted average that is slightly above the capelin price for industrial use.

Profits of each fleet (Eq. 5-20) reflect differences between revenues from sales of landings (Eq. 5-18) 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 (Eq. 5-19), which is measured as a percentage of the fishing period in which the vessels are actually engaged in harvesting activities. Vessels may enter or leave the fisheries depending on the economic returns in previous fishing periods. If harvesting operations of a fleet are profitable for five successive years, economic exploitation of the stock is increased, and the number of vessels rises by 3%. In contrast, if fishing operations are unprofitable, vessels are phased out to cut costs and the fleet size is reduced accordingly by 3% (Eq. 5-22).

In this study, we focus on profits from fishing in three different time periods of 15 years (the average lifetime of a vessel): the period 30-44 years (i.e. a time period before the change in population dynamics), 50-64 years (i.e. the time period revealing short-term impacts of the change in population dynamics), and 70-84 years (i.e. a time period in which long-term impacts of changes in population dynamics become evident). Profits are discounted at rate δ (Eq. 5-21). The control variable is the fishing effort. Economic exploitation of fish stocks is limited by stock size and population dynamics of the two species.

5.3.3 The harvesting strategies of the fishermen

The assessment in this study considers a situation where fishermen maximize profits over a number of fishing periods which is specified prior to the simulation. Three different durations of the optimization period are used in the simulations: one year, five years, and fifteen years. An optimization period of one year is the situation in which the fishermen are sure that their fishing license will be withdrawn in the near future, or that their vessel is depreciated and they have decided to retire. With a five-year optimization period, there is a reasonable certainty that fishing will be allowed for some time but not in the long run. An optimization period of fifteen years resembles the case in which the fishermen are sure that they will be able to harvest for the entire expected lifetime of the vessel.

For all vessel types the sets of fleet utilizations are determined that yield maximum profits for the whole optimization period based on the given stock sizes and population dynamics. The optimal fleet utilization for the current fishing period is applied and the stock information is updated accordingly. The optimization is repeated in each fishing period to account for the actual development of the fish stocks.

Since regulatory management measures of the cod stock affect both trawlers and coastal vessels, profits for these vessel types are maximized jointly. Profits from purse seiners used in the capelin fishery are considered separately. We assume perfect information, i.e. the stock sizes and age distributions of both species at the beginning of the harvesting period are known to the fishermen. 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 30% of the stock biomass for cod and 50% for capelin.

5.4 Results

A series of simulations was conducted to assess the consequences of changes in fish population dynamics on the fish stocks and the resulting economic impacts. In each 100 year simulation, a sudden decrease of productivity or the environmental carrying capacity was set to occur in year 50. In the following analyses, it is assumed that the change is of the same magnitude for both species. Results of simulations in which the change in population dynamics is markedly different are summarized in a subsequent section. 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, 2003c). The simulations use the same parameterizations as the analyses in chapter 4.

The economic consequences of changes in population dynamics are assessed under the assumption that all fleets determine their respective fishing effort based on profit-maximization over five years. In each fishing period, a set of fishing efforts is determined that would yield the best economic result over the following five years. The optimal effort to be applied is updated after each fishing period based on the actual stock development and the associated fishing effort is adjusted accordingly. In the sensitivity analyses, time horizons for profit maximization of one year and 15 years are considered as well.

This assessment focuses mainly on the simulations with an optimization period of five years since it can be assumed that the fisheries of cod and capelin in the Barents Sea are not going to be closed permanently in the near future. Moreover, the results of simulations with optimization periods of five years and fifteen years do not differ to a great extent which suggests that the extension of the time horizon of the profit maximization far into the future does not add to the economic success of the fisheries.

5.4.1 Impacts of a reduction of productivity

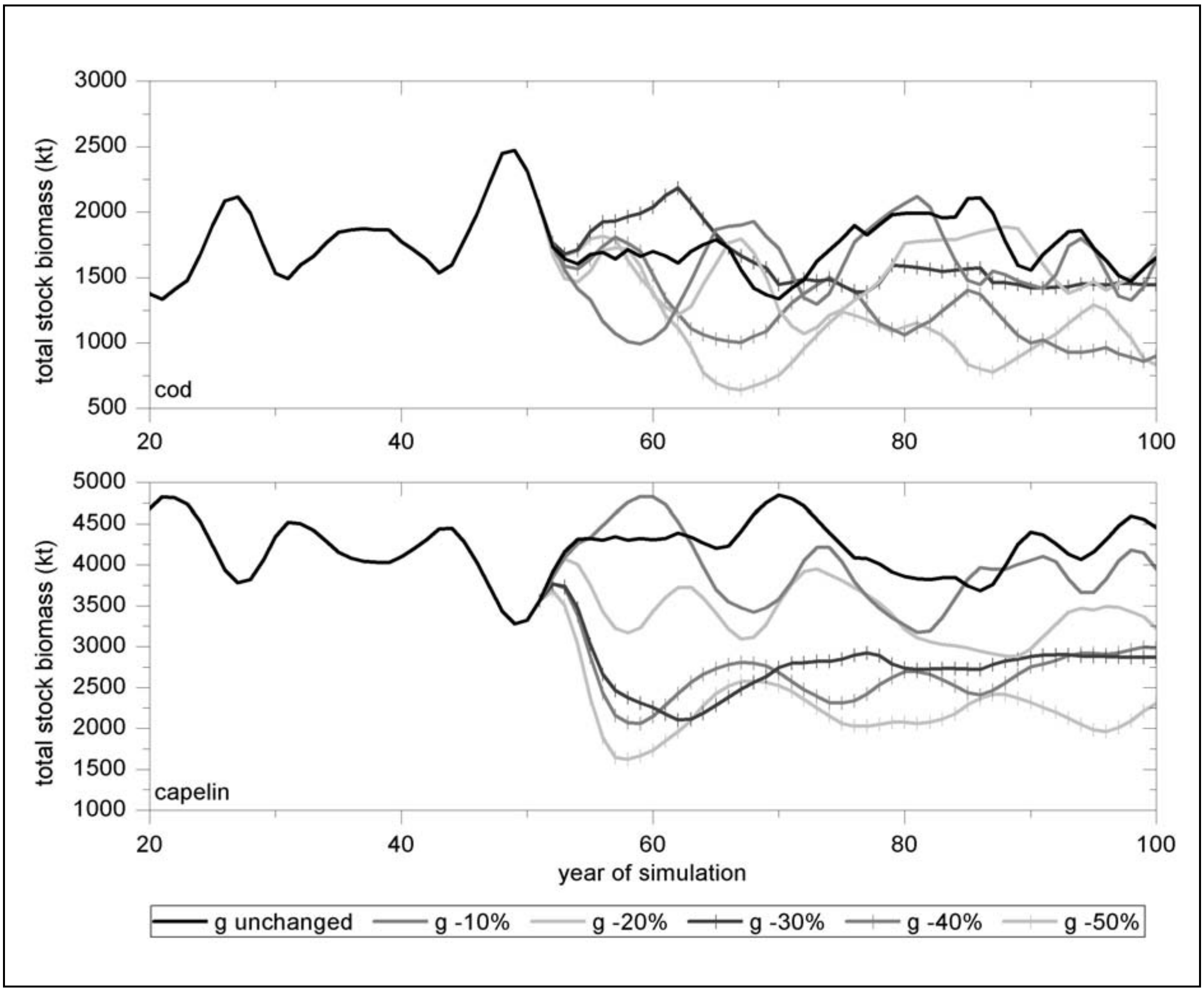

Figure 5-2: Development of the stock sizes with reduced productivities.

A decline of productivity of both species has a negative long-term impact on the stock sizes of both cod and capelin. The average cod stock size before the change in population dynamics varies between 1.25 and 2.5 million tons of biomass. It takes a reduction of the productivity of 40% or more to cause a long-term reduction of the stock size below the mark of 1.5 million tons (Fig. 5-2). The capelin stock shows some resilience to reductions in productivity. A clear decline in stock size following the change in population dynamics occurs only for a decline of the productivity of 30% or more, whereas it remains in the initial biomass range of the stock otherwise.

time period	**trawlers** (cod)		**coastal vessels** (cod)		**purse seiners** (capelin)	
change of productivity	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario
years 30-44	180.8		17.7		1058.6	
years 50-64						
g	208.2		39.0		1051.9	
g -10%	175.4	-15.8%	19.6	-49.9%	1214.1	+15.4%
g -20%	158.2	-24.0%	22.7	-41.9%	937.6	-10.9%
g -30%	99.0	-52.5%	16.1	-58.7%	607.2	-42.3%
g -40%	136.1	-34.6%	26.2	-32.8%	703.3	-33.1%
g -50%	144.0	-30.8%	13.0	-66.6%	617.2	-41.3%
years 70-84						
g	149.2		20.2		980.1	
g -10%	168.7	+13.1%	25.1	+24.1%	896.1	-8.6%
g -20%	113.7	-23.8%	13.8	-31.7%	902.7	-7.9%
g -30%	99.6	-33.2%	11.3	-44.2%	690.5	-29.6%
g -40%	72.1	-51.7%	17.8	-12.2%	658.6	-32.8%
g -50%	69.2	-53.6%	24.0	+18.4%	594.0	-39.4%

Table 5-2: Development of annual catches when productivity is reduced.

Average annual catches are generally negatively affected by reductions of productivity: starting from the situation in which the market share of trawlers dominates the cod fishery, trawl catches remain fairly stable for little changes in productivity. For large reductions, average annual catches are cut in half in the long run. The relative importance of the coastal vessels is initially very low and catches decline even further in all scenarios of reduced productivity shortly after the change in population dynamics. In later decades, coastal vessels become more important, especially if cod productivity is severely impacted (Tab. 5-2). This suggests that in periods of low cod recruitment, profit maximization over several fishing periods in the long run favors the fleet type with lower operating costs. A small change in capelin productivity has hardly any impact on the capelin fishery as catches remain stable throughout the simulation period. For reductions of 30% or more, however, capelin catches decline considerably compared to the large landings in the reference scenario.

The net present values of profits of the three fleet types develop differently over time when profits are maximized over five fishing periods. While the profitability per vessel of the trawlers is greatest when cod productivity is not or only slightly impaired, the profit index of the coastal vessels generally decreases for lower productivity (Tab. 3). If there is a large change in productivity, it sometimes happens that harvest activity and profitability shift from cost intensive trawlers to smaller coastal vessels. Also, for a larger decline of productivity the impact on the stock is big enough to cause the cod fishery to become unprofitable in the long run. The number of vessels employed in the cod fishery declines over time in all scenarios. While the number of trawlers remains stable and only increases by 40% if cod productivity is halved, coastal vessels decline by one third to one half over the simulation period.

time period	**trawlers** (cod)	**coastal vessels** (cod)	**purse seiners** (capelin)
change of productivity	profit index	profit index	profit index
years 30-44	29.9	24.1	98.3
years 50-64			
g	24.1	80.2	52.1
g -10%	60.2	23.3	52.8
g -20%	64.4	51.0	53.7
g -30%	13.0	25.0	49.4
g -40%	22.9	79.3	50.9
g -50%	11.1	24.1	48.8
years 70-84			
g	18.9	33.3	45.1
g -10%	67.4	74.6	34.6
g -20%	28.8	24.3	38.2
g -30%	17.1	23.8	19.9
g -40%	18.5	28.2	17.6
g -50%	7.5	22.6	19.9
reference values (million Nkr):			
Index 100 =	30.0	2.0	10.0
Index 0 =	-30.0	-2.0	0.0

Table 5-3: Development of the net present value of profits per vessel when productivity is reduced.

The net present value of profits of the capelin fishery remains constantly positive regardless of the scenario. This leads to a continuous increase of the number of purse seiners engaged in the capelin fishery up to a doubling at the end of the simulation period. After the change in population dynamics, the profitability of the purse seine fleet is in the long run negatively affected by the reductions in productivity (Tab. 5-3).

5.4.2 Consequences of changes of the environmental carrying capacities

A reduction of the environmental carrying capacities of both fish species has a similar effect on the stocks as a reduction in productivity: the sizes of the cod and capelin stocks decrease, but here the reduction is less pronounced. There is a generally declining trend in the cod stock biomass for decreased carrying capacities. However, for a change in productivity by 30% or less, the stock size remains within or close to its fluctuation range in the reference scenario (Fig. 5-3). Only a 50% reduction of the carrying capacity leads to lower biomass levels from which the stock cannot rebuild. In this scenario, the stock declines a little more than 1.0 million tons and remains stable at this reduced level for the rest of the simulation period.

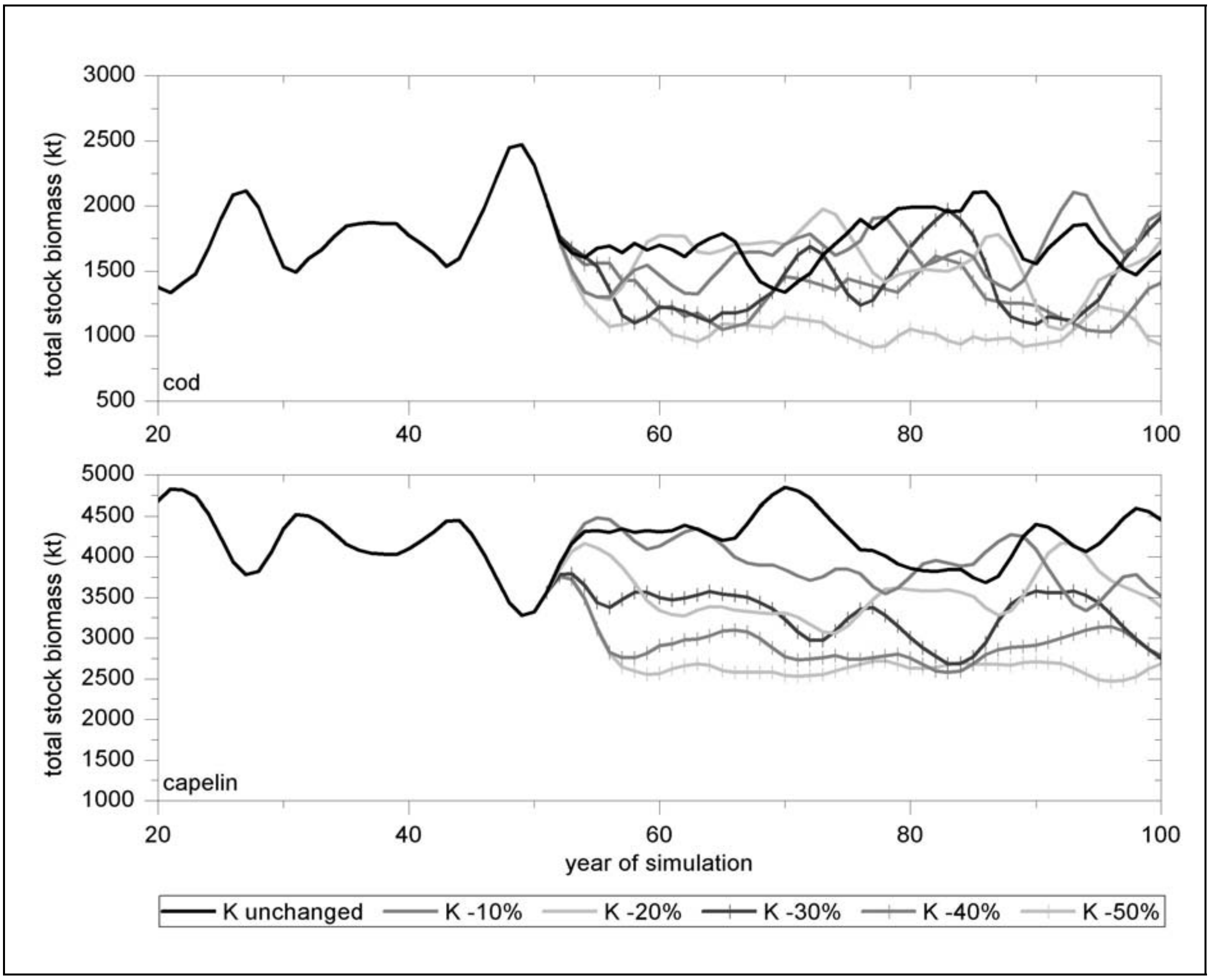

Figure 5-3: Development of the stock sizes with reduced carrying capacities.

The impact of a reduced carrying capacity on the development of the capelin stock is rather weak. With the stock biomass already fluctuating substantially in the reference scenario, only large reductions of the carrying capacity cause the stock size to permanently deviate downward from the original range of fluctuation (Fig. 5-3). After the initial reduction of the capelin stock arising from the changed carrying capacity, the stock biomass remains stable at the new level, which amounts to 2.5 to 3.5 million tons regardless of the magnitude of the decline of the carrying capacity.

A lower cod carrying capacity generally leads to smaller annual catches by trawlers. However, the decline exceeds 25% only if the carrying capacity is halved (Tab. 5-4). In contrast, average annual catches by coastal vessels even increase in the long run, as the less cost-intensive coastal vessels can even take over market shares from trawlers.

time period	**trawlers** (cod)		**coastal vessels** (cod)		**purse seiners** (capelin)	
change of the carrying capacity	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario	average annual catch (1000 t)	change from reference scenario
years 30-44	180.8		17.7		1058.6	
years 50-64						
K	208.2		39.0		1051.9	
K -10%	200.2	-3.8%	6.8	-82.5%	1134.5	+7.9%
K -20%	160.3	-23.0%	21.9	-44.0%	932.4	-11.4%
K -30%	174.7	-16.1%	18.8	-51.8%	971.2	-7.7%
K -40%	162.2	-22.1%	17.5	-55.1%	824.7	-21.6%
K -50%	123.7	-40.6%	29.9	-23.4%	829.0	-21.2%
years 70-84						
K	149.2		20.2		980.1	
K -10%	213.0	+42.8%	22.3	+10.2%	915.1	-6.6%
K -20%	141.1	-5.4%	22.9	+13.1%	830.7	-15.2%
K -30%	112.4	-24.7%	36.9	+82.4%	719.6	-26.6%
K -40%	122.9	-17.6%	5.1	-75.0%	668.3	-31.8%
K -50%	70.5	-52.8%	32.1	+58.7%	752.5	-23.2%

Table 5-4: Development of annual catches when the environmental carrying capacity is reduced.

Catches of capelin are similarly affected by a change in the carrying capacity of the species as by a reduction of productivity. In the first few years after the change in population dynamics, average catches decline by a little more than 20% compared to the reference scenario (Tab. 5-4). In later years, average annual capelin catches decline slightly further but the overall reduction remains less than a third from the original harvest amount in all scenarios.

A reduction of the environmental carrying capacities has a lesser impact on profits than a decline of productivity. The trawlers’ profits remain at least stable in all scenarios (Tab. 5-5). Initially, a change in the carrying capacity is unfavorable for the coastal vessels. However, the profit index of the coastal vessels develops positively in the long run. The profitability of the purse seine vessels is stable throughout the simulation period and develops similarly to the scenarios with a changing productivity. It has to be noted that the development of the fleet sizes is essentially the same as for the change in productivity: the number of trawlers hardly changes, coastal vessels decline by one third to one half, while the capelin fishery can expand, particularly in the last decades of the simulation period.

time period	**trawlers** (cod)	**coastal vessels** (cod)	**purse seiners** (capelin)
change of the carrying capacity	profit index	profit index	profit index
years 30-44	29.9	24.1	98.3
years 50-64			
K	24.1	80.2	52.1
K -10%	74.1	26.0	54.1
K -20%	50.3	79.4	53.3
K -30%	30.1	24.9	50.3
K -40%	24.1	57.4	50.4
K -50%	73.6	31.2	52.5
years 70-84			
K	18.9	33.3	45.1
K -10%	99.3	123.0	26.1
K -20%	19.1	120.0	20.2
K -30%	32.9	79.0	20.1
K -40%	99.2	31.6	17.8
K -50%	52.3	94.7	18.5
reference values (million Nkr):			
Index 100 =	30.0	2.0	10.0
Index 0 =	-30.0	-2.0	0.0

Table 5-5: Development of the net present value of profits per vessel when the environmental carrying capacity is reduced.

5.4.3 Combination of both effects

So far, we considered the cases in which the change in population dynamics is of the same extent for both species. If the change in productivity or carrying capacity is much greater for one species, the resulting scenarios can be divided into two categories: (1) if the change in the cod stock is much greater than in the capelin stock, profitable harvesting of cod is no longer possible in the long run. The capelin stock remains at initial stock levels or even increases in some scenarios which helps the capelin fishery since a larger share of the stock is available for exploitation because of decreased losses from predation. (2) Vice versa, a much larger change in population dynamics of capelin practically leads to a collapse of the capelin stock. The smaller capelin stock faces a stable cod population which drives down the capelin stock size in addition to harvest activities. The cod fishery is not positively affected by such a development. However, economic results remain stable throughout the simulation period.

We also explored the possibility that a change in environmental conditions causes both productivity and the environmental carrying capacities to be affected at the same time so that both changes in population dynamics were combined to assess how a simultaneous change of these quantities affects economic returns to the cod and capelin fisheries. Results show that the profits from fishing are only marginally affected when both changes in population dynamics occur concurrently as long as the magnitude of the changes in population dynamics is 20% each or less. In these cases, the amount of fish landed and the net present value of profits fall within the same range as in the scenarios described above. On the other hand, if the reduction of productivity and the carrying capacities exceeds 30% each, there are substantial impacts on both stocks. The biomass of both stocks declines by more than two thirds and this in turn has negative impacts on the fisheries. In the period of interest between the years 70 and 84, the cod fishery almost comes to a complete standstill regardless of the time horizon of profit maximization. The returns of the capelin fishery also decrease substantially but remain slightly positive, which is not sufficient to compensate for the deficits accrued by the cod fishery.

5.5 Sensitivity analyses

In the sensitivity analyses, we explore the influence of changes in key economic parameters on the stocks and their respective fisheries, viz. the average market price of capelin and the discount rate. Therefore, in contrast to the scenarios of changes in population dynamics, the nature of the stock-recruitment relationship does not change in the sensitivity analysis. Nonetheless, the economic development of the fisheries varies distinctly depending on the setting of these key economic parameters.

5.5.1 Influence of the share of capelin devoted to human consumption

Traditionally, most of the Norwegian capelin catches is used in the production of fish meal and oil. However, in recent years there has been an increase in the amount of capelin that is exported and used for human consumption. Close to 50% of the capelin landed by Norwegian fishermen was exported in 1999 (Statistisk Sentralbyrå, 2000) with the market price for capelin that is exported being up to seven times as high as the price for capelin that is used industrially (Fiskeridirektoratet, 2001).

In the previous analyses, it was assumed that capelin is entirely harvested for industrial purposes and the respective market price was used. Here, the share of capelin used for human consumption is set to different levels between zero and 50%. Consequently, the market price of capelin increased with more capelin being used for consumption. It is assumed that the market price for capelin that is used industrially $P_{cap,ind}$ is Nkr 0.60 per kg while the market price for capelin that is used for consumption $P_{cap,hum}$ is Nkr 4.20 per kg, so the average price level of capelin in the simulations turns out to be between 0.60 and 2.40 Nkr per kg.

average market price of capelin (Nkr / kg)	*years 30-44* profit index	*years 50-64* profit index	*years 70-84* profit index
1-yr. optimization			
0.60	159.6	87.6	79.2
0.96	264.7	175.8	112.5
1.32	396.6	168.7	151.9
1.68	455.2	303.6	189.5
2.04	536.2	350.8	233.1
2.40	485.8	475.1	309.0
5-yr. optimization			
0.60	98.3	52.1	45.1
0.96	197.6	84.9	53.2
1.32	144.2	96.6	86.4
1.68	234.5	132.6	103.6
2.04	409.4	281.3	157.8
2.40	294.2	245.8	187.6
15-yr. optimization			
0.60	43.0	32.5	17.0
0.96	51.6	76.5	23.1
1.32	136.2	76.1	39.9
1.68	164.2	66.0	33.8
2.04	177.0	111.2	97.8
2.40	390.1	255.9	108.3
reference value (million Nkr):	Index 100 = 10.0		

Table 5-6: Influence of an increase of the average market price of capelin on profits from fishing

Simulations with different price levels of capelin show that the amount of capelin caught in each fishing period hardly varies despite the increased value of the resource. This can be explained by the fact that in each case the fleet utilization of the purse seine vessels is quite high so there is only little room to expand the fishing effort. However, the net present values of profits of the capelin fishery increase substantially (Tab. 5-6) for a higher average fish price. Already if only 10% of the capelin catches are used for human consumption, the average capelin price increase causes the net present values of profits in the capelin fishery to increase substantially, compared to the scenario in which all capelin is harvested for industrial processing. The overall profits from fishing are higher if the profit-maximizing harvest strategy considers only a short period of time since this causes fishermen to harvest more aggressively which leads to higher annual catches to start with.

So regardless of the optimization period, it is very advantageous for the capelin fishery to have part of the landings sold for human consumption. However, it has to be noted that only if profits are optimized without any future considerations, the economic result remains high in the later decades of the simulations. For longer optimization periods, the profitability decreases over time due to the increasing tendency to postpone catches to allow for further stock growth. This strategy leads to diminishing returns in the long run since capelin that is not harvested serves as additional food source for cod. The cod fishery is affected little by changes in the price level of capelin as landings and profits from fishing hardly differ in these simulations.

5.5.2 Influence of the discount rate

Since the objective is to maximize the discounted profits over a given optimization period, variations in the discount factor have an influence on the optimal harvesting strategy and therefore on landings and profits. In order to determine the influence of the discount rate on the profits from fishing, simulations of the reference scenario are conducted with various discount rates ranging from 1% to 15% for optimization periods of one, five and 15 years. In this sensitivity analysis no change in population dynamics of fish occurs to ensure comparability between the scenarios. The assessment of the influence of the interest rate focuses of the time period between years 30 and 44, which is representative for all three periods of interest.

For an optimization period of only one year, the returns from fishing of the fleets harvesting cod are highest for an interest rate of 7% (Tab. 5-7). Because of the considerable interannual variability of cod landings, the profits of the trawl fishery are also quite large for higher interest rates, when good years of fishing at the beginning of the period of interest cannot be offset by less successful years shortly afterwards. The generally low profitability of the coastal vessels confirms that the strategy of utilizing mostly trawlers to harvest cod and leaving the coastal vessels with constantly small landings is independent of the interest rate.

In contrast, the profits from harvesting capelin are high and stable for practically all discount rates.

discount rate	**trawlers** (cod) profit index	**coastal vessels** (cod) profit index	**purse seiners** (capelin) profit index	**all fleets** (cod & capelin) profit index
1-yr. optimization				
1 %	46.0	12.1	77.0	69.1
3 %	47.4	8.5	78.2	70.7
5 %	55.5	16.1	74.8	78.2
7 %	71.4	22.1	79.8	96.2
9 %	50.0	7.4	88.4	76.7
11 %	54.7	19.7	74.7	77.6
13 %	65.3	22.4	75.0	88.5
15 %	41.6	9.6	82.4	66.4
5-yr. optimization				
1 %	22.6	90.3	22.9	32.9
3 %	30.2	24.2	41.7	42.4
5 %	55.0	36.7	30.3	64.2
7 %	29.9	24.1	49.2	44.5
9 %	120.2	25.4	30.3	128.6
11 %	50.9	22.2	42.9	63.3
13 %	21.7	24.1	24.5	28.1
15 %	11.7	34.6	37.3	23.1
15-yr. optimization				
1 %	11.2	28.0	12.6	14.0
3 %	138.8	297.5	9.5	158.4
5 %	14.6	25.6	13.5	17.5
7 %	16.6	47.3	21.5	23.5
9 %	9.9	23.6	23.2	15.8
11 %	74.7	50.8	16.5	80.3
13 %	222.4	22.4	8.9	223.6
15 %	41.2	22.1	17.3	45.1
reference values (million Nkr):				
Index 100 =	30.0	2.0	20.0	30.0
Index 0 =	-30.0	-2.0	0.0	-30.0

Table 5-7: Influence of the discount rate on profits from fishing

The situation is different if the optimization period is five or fifteen years. The shift of harvest activities from trawlers to coastal vessels becomes apparent in the improvement of the general profitability of the coastal vessels while the net present values of profits of the trawlers becomes negative more often (Tab. 5-7). The profits of the capelin fishery remain positive but are distinctly smaller than in the optimization over a short time horizon. Just as observed for the cod fishery, this is due to fishing periods in which harvesting activities are skipped to increase the profitability in subsequent fishing periods.

5.6 Discussion and conclusion

The simulations show that adverse changes in fish population dynamics have a mostly negative long-term impact on the stock sizes of both fish species assessed. As in the cod stock, the extent of the decline in stock size is smaller for the change in the carrying capacity than for the reduction in productivity. This has to do with the interaction between the two species in the simulation model: when the carrying capacities of the two species are reduced, the downward trend of the cod stock size is more pronounced than for the change in productivity, causing a release of the predation pressure. This in turn has an offsetting effect on the capelin stock which can recover back close to the range of fluctuation prior to the change in population dynamics despite a sometimes significantly lower carrying capacity.

The smaller stock sizes generally lead to decreased landings. However, the development of harvests is different for all fleets. The trawlers are almost always negatively affected whereas the market share of the coastal vessels actually increases in the long run, particularly for changes in the carrying capacity, owing to a shift of fishing effort in the cod fishery away from the cost-intensive trawlers to the smaller coastal vessels. The capelin fishery also experiences somewhat smaller harvests after the adverse change in population dynamics. However, this development has only little influence on the profitability of the capelin fishery.

Despite the large variability in the profit indices of all fleets, the generally reduced landings of both species affect the profits of the fisheries in particular ways. The overall development of the trawlers’ profits is shows no clear trend: compared to the reference scenario, in which the net present values of profits are quite low to start with, the trawlers’ profits remain stable regardless of the extent of the change in population dynamics. In some scenarios, the profits in the periods of interest can even increase despite the impaired stock dynamics. In the long run, the relative importance of the coastal vessels increases in many scenarios and so do their profits. This development is much more pronounced in the scenarios of changes in carrying capacity, particularly in years 70 through 84.

The profits of the capelin fishery remain positive throughout the simulation period and show a similar development for both kinds of change in population dynamics. Shortly after the changes, there is only little impact on the profitability of the capelin fishery. Only some decades later the profits per vessel decline for pronounced reductions of productivity or carrying capacity. It has to be noted, however, that the decline in profits per vessel is also influenced by the growing number of vessels employed in the capelin fishery that can be generally observed.

The simulations show that the length of the optimization period has a distinct impact on the results: first of all, the shorter the optimization period, the more aggressive the harvesting strategy becomes. Overall landings and net present values of profits are highest if the optimization period is only one year as there is no deference of harvesting activities. This setup greatly favors trawlers over small coastal vessels due to the larger catch efficiency of the former as the standing cod biomass is lower than in the simulations with an optimization period of several years. The longer the optimization period, the greater the importance of the coastal vessels in the cod fishery becomes. This is because with long optimization periods, the frequency of harvesting periods in which catches are deferred increases compared to short optimization periods and such strategy favors the fleet type that has the lowest cost per unit effort. The capelin fishery also obtains the best economic results for short optimization periods, those in which the cod stock biomass are lowest. This way, the losses to predation are minimized and it is easiest to maintain large landings and stable profits.

A comparison of the results of the simulations with ICES stock assessment data shows that for the 5-year profit maximization the average stock size of cod in the model is slightly overestimated while the calculated catch sizes are somewhat lower than the officially published values. Currently, the cod stock in the Barents Sea has a biomass (age 3 and older) of about 1.5 million tons and cod landings total roughly 450 000 tons, most of which is caught by trawlers (cf. ICES, 2003a; Michalsen, 2004). In the simulations, the cod stock biomass varies between 2 and 3 million tons in the reference scenario and annual harvests amount to somewhere around 200 000 tons, with trawler accounting for most of the total cod catches.

However, the model results for the capelin stock and the amount of capelin harvested deviate to a larger extent from the actual development: The model generally overestimates the capelin stock size which causes the catch size of capelin by the purse seine vessels and the subsequent economic result of this fishery to be too high. The consequence of this overestimation is that the importance of the capelin fishery in the profit maximization is too large compared to the cod fishery. If the capelin biomass were lower and subject to a larger variability than in the current model version, the role of the fleets harvesting capelin would be weakened relative to the fleets harvesting cod assuming a profit-maximizing harvest strategy is applied.

The discrepancy between the model and reality occurs because the model only considers the predator-prey relationship between cod and capelin. While it is necessary to consider this important interaction between the two species, interactions of capelin with other species are neglected. This omission is the main reason for the deviation of model results from reality. One possibility to increase the quality of simulation results of capelin is to include the occurrence of young herring (*Clupea harengus*) in the Barents Sea in the model. Young herring feed extensively on capelin larvae, and their presence could result in a severely reduced recruitment success of capelin (Gjøsæter & Bogstad, 1998). This would lead to a significantly reduced capelin stock that can only rebuild when the young herring have left the Barents Sea to join the adult part of the herring stock in the Norwegian Sea.

The strategy of periodic harvesting when conditions are best suited for fishing may yield particularly large catches in some years but in several ways it can hardly be considered as optimal: if the stocks are exploited very heavily in some fishing periods, this has negative impacts on the spawning stock biomasses and thus on the capabilities to replace the losses from harvesting. Furthermore, the frequent occurrence of fishing periods in which there is no fishing activity of a given fleet makes it necessary to use labor punctually instead of continuously. In reality, this would mean hiring a large number of fishermen for a short period of time and then laying them off again if it is optimal to cease fishing again soon afterwards. This is by no means a practical way to deal with the variability in the exploitation of commercial fish species.

Despite the simplifications embodied in our simulation model, it is possible to obtain some insights about the possible consequences of a reduction in productivity or the environmental carrying capacities on the cod and capelin stocks in the Barents Sea and the catches of their fisheries under profit-maximizing harvesting strategies. Further development of the model will be conducted in order get a more differentiated view of the economic consequences caused by a change of the population dynamics of the exploited fish stocks arising from changes in climatic or hydrographic conditions.

5.7 Appendix 1: List of symbols used in the model

symbol	**meaning**
a	index denoting the age class
A	highest age class of a species
B	biomass
cap	index referring to capelin
cod	index referring to cod
D	prey density
d	discount rate
e	fleet utilization
g	productivity
h	harvest
harv	index denoting the stock size after harvesting has been considered
hum	index referring to human consumption
i	index denoting the fleet type
ind	index referring to industrial use
init	index referring to the beginning of a fishing period
K	carrying capacity
n	number of individuals in an age class
P	fish price
pred	index denoting the stock size after harvesting and predation have been considered
q	catchability coefficient
r	revenue
R	recruitment
s	index denoting the species
SSB	spawning stock biomass
sw	spawning weight
t	index denoting the fishing period
v	number of vessels
w	weight
α	parameter used in recruitment function
β	parameter used in recruitment function
δ	discount factor
θ	variable costs
$\kappa1$	rate of predation
$\kappa2$	parameter used in calculation of predated biomass
μ	share of mature individuals
π	profit per fishing period
Π	net present value of profits over a 15-year period
φ	fixed costs
χ	natural survival rate
ψ	total costs
ω	cost per unit effort

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

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This chapter has been submitted for publication.

6.1 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 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 both adaptive and profit-maximizing harvesting strategies. 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, profit maximization leads to more stable economic results of these fisheries than the adaptive fishing strategy.

6.2 Introduction

The thermohaline circulation (THC) 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). In the Norwegian and Barents Seas, a reduced THC would result 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).

On the other hand, water temperatures in the spawning ground of Arcto-Norwegian cod (*Gadus morhua*) and capelin (*Mallotus villosus*) are likely to increase as a consequence of anthropogenically induced global warming and 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 & Sundby, 2003) for a given spawning stock biomass. 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 Arcto-Norwegian cod stock.

The capelin stock would also be affected, since the development of capelin as a planktivorous species is influenced by the abundance of zooplankton in the Barents Sea. As abundance of the dominant zooplankton in the Barents Sea *Calanus finmarchicus* is positively correlated with temperature (Pershing *et al*., 2004), a warming trend in the Barents Sea would potentially increase this important food source for capelin (Dalpadado *et al*., 2003). However, warmer temperatures also increase the likelihood of young herring preying extensively on capelin larvae in the Barents Sea, thus significantly reducing recruitment success of individual year classes (Gjøsæter & Bogstad, 1998)

Changes in the stock development of cod and capelin inevitably have an effect on the fisheries of these species. This study assesses the possible economic impacts of changes in THC strength on the Barents Sea cod and capelin fisheries using a bioeconomic simulation model, analyzing scenarios of climate change and THC development generated with the CLIMBER 3α model (Montoya *et al*., 2005). The application of actual climate change scenarios extends the analyses of the previous two chapters of this thesis, 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 Arcto-Norwegian cod and Barents Sea capelin stocks.

6.3 Materials and methods

6.3.1 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 has 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 determined for two different harvesting strategies: adaptive behavior of the fishermen and profit-maximizing harvesting. More detailed descriptions of the model are given in chapters 4 and 5.

6.3.1.1 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.

(6-1) $$R_{s,t} = f\left(T_t, SSB_{s,t}\right) = \left(\rho_s T_t + \sigma_s\right)\varepsilon_{s,t}\left(SSB_{s,t}\right)$$

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.

Since the temperature dependence of capelin recruitment follows the same pattern, the above functional form is used for both species. However, capelin recruitment is also critically dependent on the presence of young herring in the Barents Sea (Gjøsæter & Bogstad, 1998). In these simulations, it is assumed that capelin recruitment is reduced by 90% if herring are present, and that the likelihood of herring being present in a given year increases stepwise with temperature 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), 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

$$\chi_{s,a,t} = 0.81 - 0.08\left(THC_{ref} - THC_t\right) \tag{6-2}$$

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

6.3.1.2 The fisheries

The weight of the entire catch is determined from the number of fish caught in each fishing period. It is assumed that the demand curve is perfectly elastic, i.e. the market prices for both species remain constant regardless of the amount of fish landed. 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. Vessels may enter or leave the fisheries depending on the economic returns in previous fishing periods. If harvesting operations of a fleet 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%.

Profits are discounted at rate 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.

6.3.1.3 The harvesting strategies of the fishermen

In the simulations, two different harvesting strategies are considered. One is adaptive harvesting, in which each fleet's fishing effort is adjusted after each fishing period according to returns from fishing in the previous fishing period (see chapter 4). 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 maximization of profits over a number of fishing periods which is specified prior to the simulation (see chapter 5). In each fishing period, a set of fishing efforts is determined that would yield the best economic result over the whole optimization period. The optimal effort to be applied is updated after each fishing period based on the actual stock development and the associated fishing effort is adjusted 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 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 because of the diminishing importance of additional fishing periods included in the optimizations due to discounting. Therefore, adding more fishing periods to the optimizations gains little extra information and the results from simulations with a four-year optimization period can be considered characteristic for a long-term profit-maximizing harvest strategy.

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.

6.3.2 Linking of the bioeconomic model to scenarios of environmental change

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.*, 2006). 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. 6-1). 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.

In the model scenarios, the spring temperature in the spawning grounds of Arcto-Norwegian cod and capelin is determined by

$$(6\text{-}3) \quad T_{sc,t} = \bar{T}_{1940-1990} + \mathrm{E}_t + \Delta T_{sc,t}$$

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. 6-2) is added.

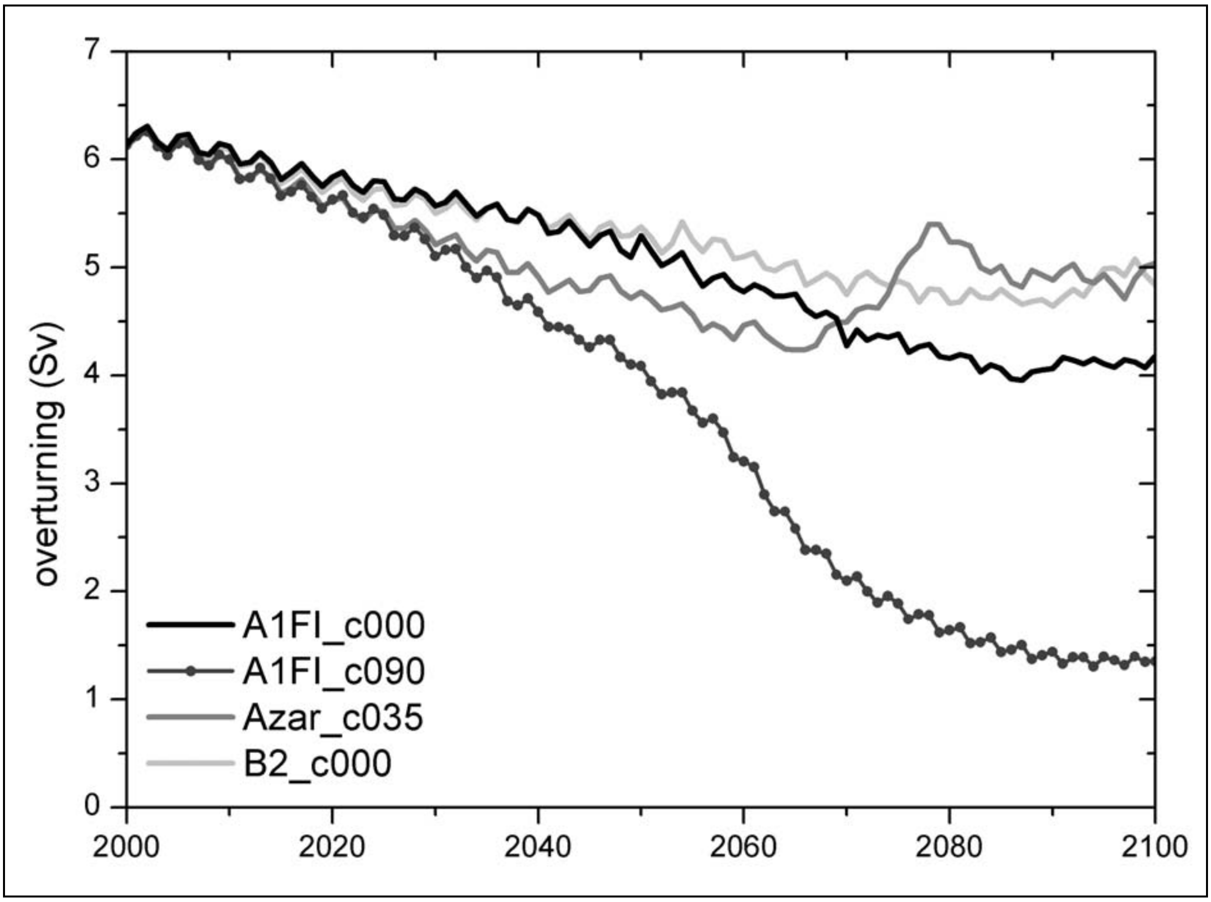

Figure 6-1: THC strength in the four scenarios during the 21st century.

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*., 2006), 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 Arcto-Norwegian cod (Planque & 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, spawning conditions also improve with higher temperatures, but increased threats to larvae by a more frequent presence of herring and an increased predation pressure by cod (Hjermann *et al*., 2004a) 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.

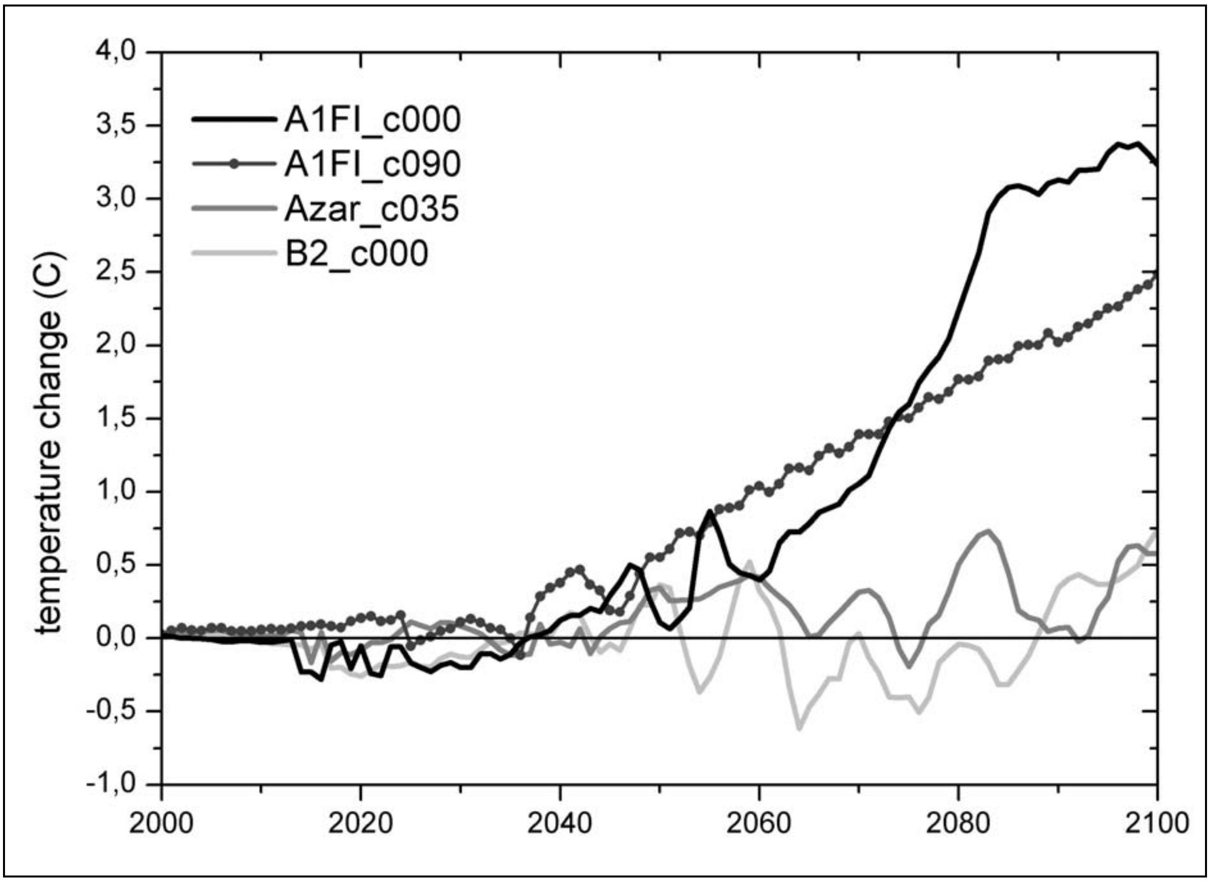

Figure 6-2: Change of spring temperature in the spawning grounds with respect to the 1961-1990 average.

6.4 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, 2003c). The simulations use the same parameterizations as the analyses in the previous two chapters.

6.4.1 Impacts on fisheries using adaptive strategies

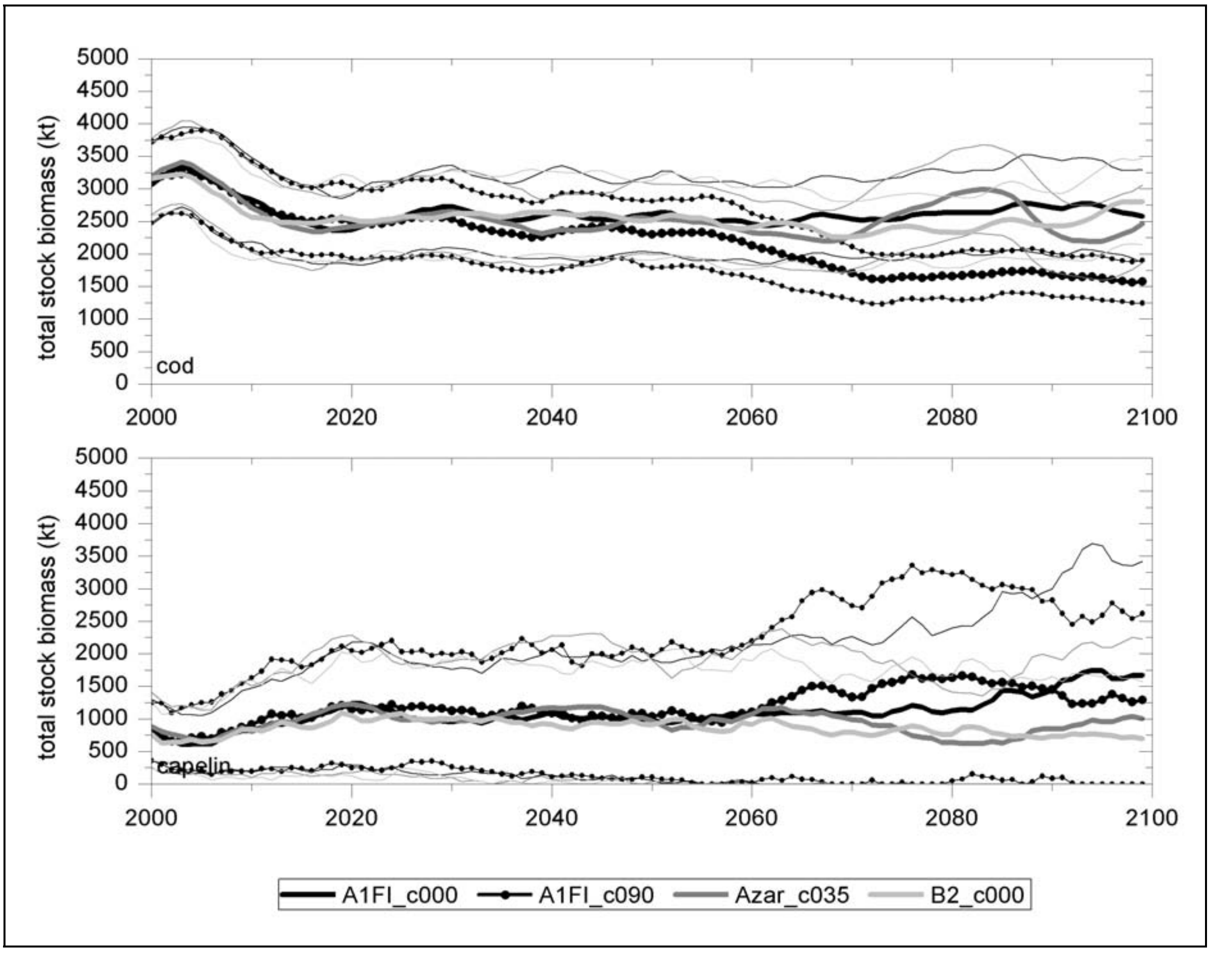

Figure 6-3: Development of the stock biomasses if fishermen employ adaptive harvesting strategies. Thick lines denote the average of the 100 runs in each ensemble, thin lines the corresponding standard deviations.

The strength of the THC has a profound impact on the long term development of the Arcto-Norwegian 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. 6-3) if fishermen follow an adaptive harvesting strategy. In case the THC weakens considerably, the cod stock size declines in the long run, starting in the middle of the simulation period but is not in danger of extinction. On average, the capelin stock size is quite stable in all scenarios. The release of predation pressure due to the declining cod stock in the A1FI_c090 scenario allows for a larger capelin stock in the second half of the 21st century. However, it needs to be noted that the variability in the development of the capelin stock is extensive and the probability of complete stock failure lies between 31% for the A1FI_c090 scenario and 46% in the B2_c000 scenario, which is a substantial obstacle for a profitable exploitation of the stock.

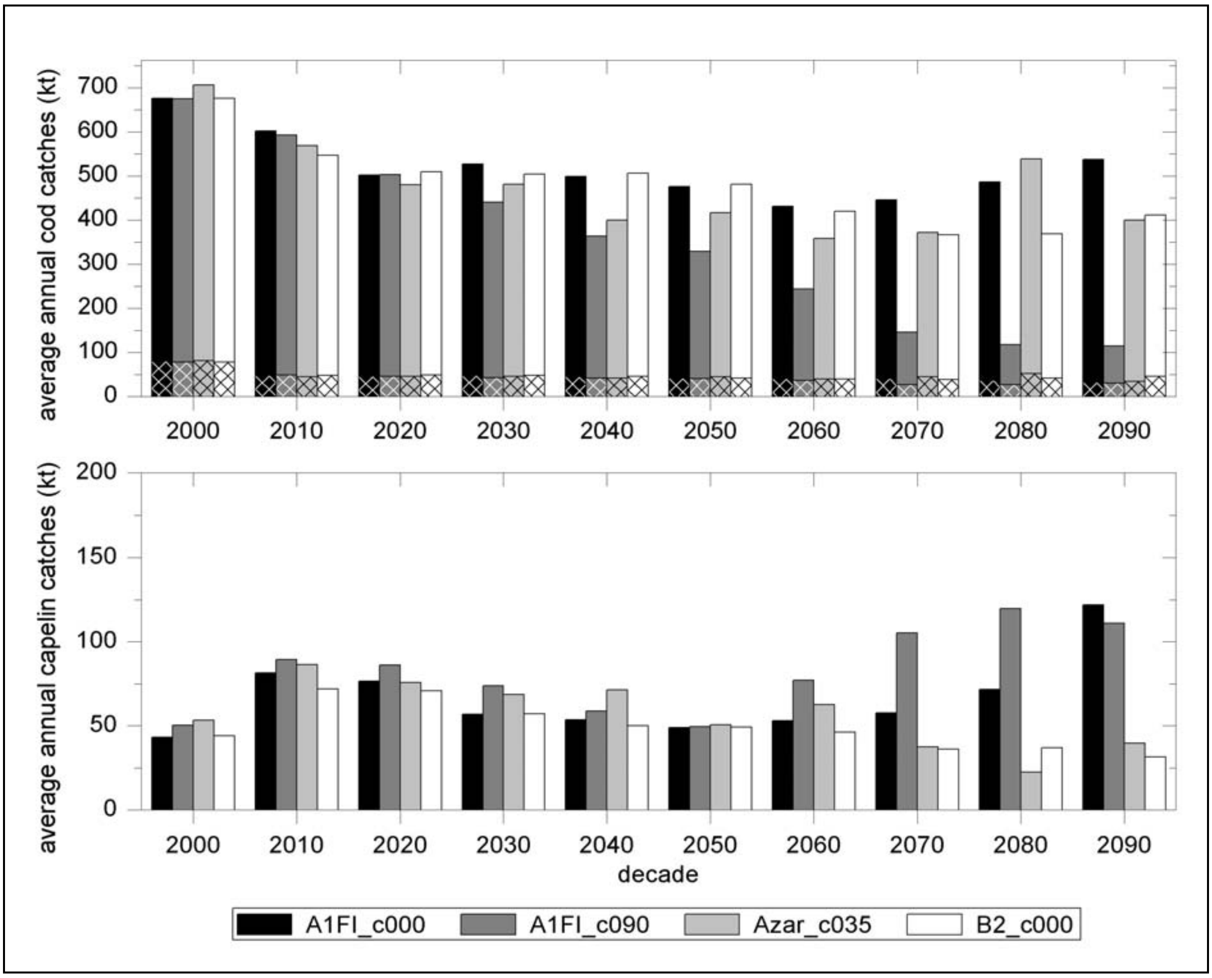

Figure 6-4: Average annual catches of all fleets in each decade if adaptive harvesting strategies are used. Cod catches: regular columns denote trawl catches, shaded columns catches by coastal vessels.

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 500 000 tons. The warming in the A1FI_c000 scenario helps the fishery, as landings are generally highest in this scenario (Fig. 6-4). The Azar_c035 and B2_c000 scenarios both lead to more or less the same harvest amounts with an increased variability in the Azar_c035 scenario in the second half of the 21st century. 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.

	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	2490.83	67	2500.89	66	2674.91	67	2491.88	66
2010s	1955.65	76	1918.56	75	1766.94	76	1655.83	75
2020s	1302.57	84	1301.15	84	1181.49	84	1339.15	84
2030s	1324.78	92	842.49	91	1079.54	91	1210.97	91
2040s	1086.34	98	357.69	95	549.57	96	1126.96	98
2050s	877.27	104	118.31	97	585.52	99	902.81	103
2060s	563.03	108	-371.07	96	207.17	103	505.85	108
2070s	581.22	111	-780.49	89	308.40	103	182.35	110
2080s	763.60	114	-759.01	80	1193.50	106	177.36	110
2090s	983.46	118	-644.14	70	320.10	111	403.54	111
coastal vessels								
2000s	-36.87	469	-51.42	468	-37.18	470	-62.44	470
2010s	-257.77	455	-246.79	454	-277.66	454	-235.50	452
2020s	-165.04	424	-167.43	423	-149.42	423	-148.54	425
2030s	-133.08	400	-141.29	398	-129.62	401	-117.56	403
2040s	-117.63	380	-93.37	375	-107.51	380	-116.22	385
2050s	-113.89	360	-82.80	358	-76.22	363	-120.22	366
2060s	-92.73	342	-98.91	343	-97.74	348	-106.78	348
2070s	-86.12	329	-120.76	324	-38.37	332	-77.77	332
2080s	-119.69	314	-90.27	298	-24.42	327	-43.73	319
2090s	-148.08	297	-68.04	277	-119.39	318	-29.82	309
purse seiners								
2000s	-7.40	68	-3.83	68	-2.27	68	-6.71	68
2010s	16.70	63	21.01	64	19.84	64	11.77	63
2020s	15.69	62	20.35	63	15.15	62	12.46	61
2030s	4.82	61	13.73	63	11.43	62	5.40	61
2040s	3.48	61	5.60	63	13.00	63	1.71	60
2050s	1.49	60	0.98	62	1.03	63	1.74	60
2060s	3.86	60	17.45	61	8.47	62	0.25	60
2070s	6.79	60	33.70	62	-5.58	62	-5.26	59
2080s	15.14	60	40.69	63	-13.12	60	-4.58	59
2090s	43.83	61	34.56	66	-2.43	58	-7.47	58

Table 6-1: Average annual profits and fleet sizes in each decade if an adaptive harvesting strategy is employed.

On average, the capelin fishery maintains very low catch levels throughout the simulation period. Annual catches rarely exceed 100 000 tons (Fig. 6-4), with the largest harvest amounts arising in the A1FI scenarios, in which conditions become considerably warmer in the latter half of the simulation period. The low average catches are a consequence of the high frequency of stock failure, which causes the capelin fishery to remain closed for substantial periods of time in more than half of the simulations in each ensemble.

The net present values of profits of the three fleet types develop quite differently in the four scenarios analyzed (Tab. 6-1). In the cod fishery, average annual profits decline over time in all scenarios, owing to the large overall profits in the first two decades of the simulations. While profits of trawlers remain at a high level in the A1FI_scenario, the drop in profits is much more pronounced. 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. 6-4). 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.

The exploitation of the capelin stock using purse seiners has little economic significance if adaptive harvesting strategies are used, as profits are close to zero in all scenarios throughout the simulation period (Fig. 6-4). The profitability of the capelin fishery increases in the A1FI_c090 scenario, as the reduction in the cod stock helps the capelin stock to expand, leaving additional capelin to be caught. The fleet size shows only little variability, as there is no need to expand the fleet if profits are only slightly positive. This economic insignificance has to do with the fact that if this harvesting strategy is applied, the capelin stock reaches dangerously low stock sizes regularly, so harvesting activities have to be interrupted frequently as a consequence of management measures. The closures of the fishery lead to substantial losses as the fixed costs for fleet maintenance are also considered in periods when there is no harvesting, and proceeds from catch sales are just large enough to cover costs for all fishing periods in most cases.

6.4.2 Impacts on profit-maximizing fisheries

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.

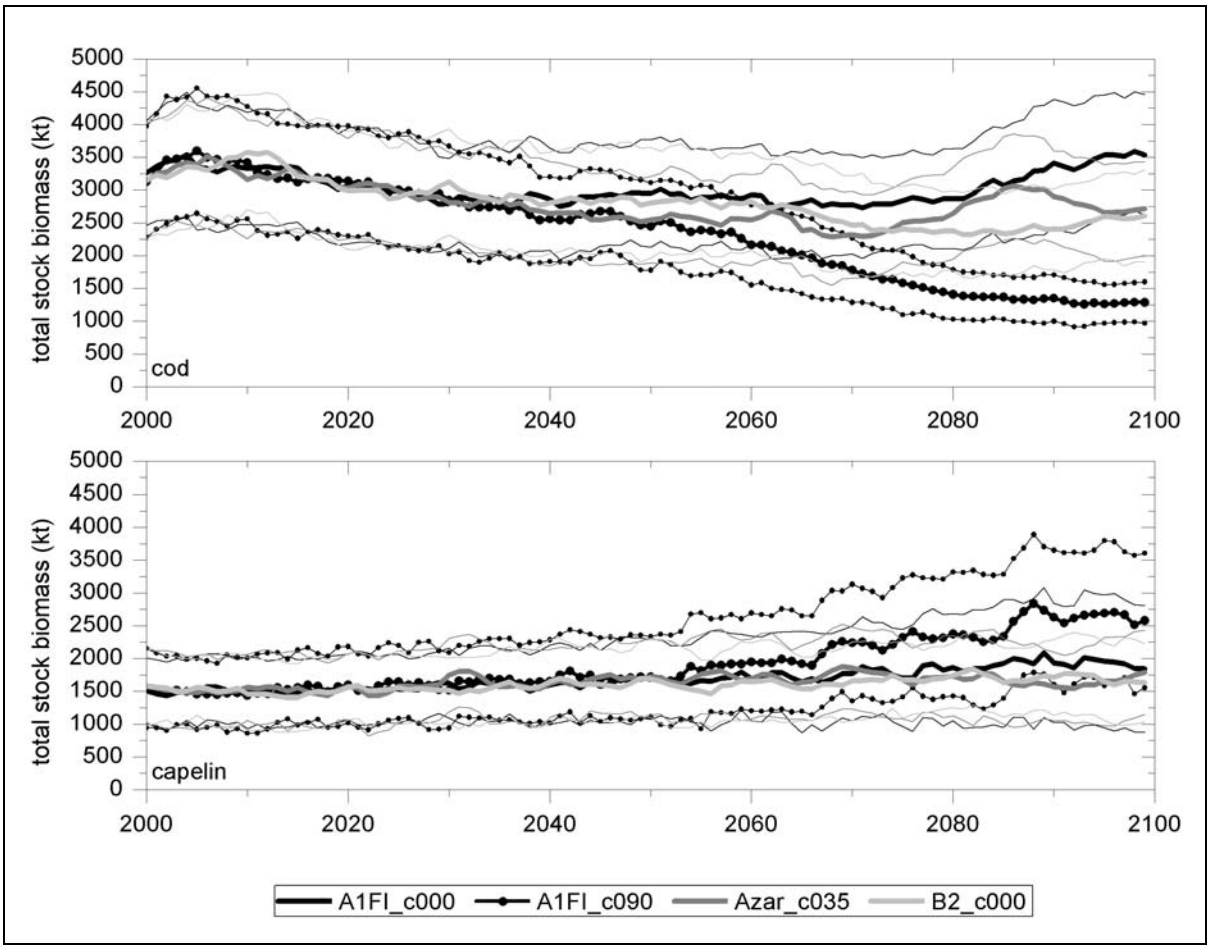

Figure 6-5: Development of the stock biomasses if fishermen employ profit-maximizing strategies. Thick lines denote the average of the 100 runs in each ensemble, thin lines the corresponding standard deviations.

In all scenarios, the cod stock qualitatively develops similarly under profit-maximizing fisheries as under adaptive harvesting. However, the A1FI scenarios produce more pronounced extremes with profit maximization. While warming is beneficial for the stock to the extent that the average stock size reaches 3.5 million tons of biomass by the end of the simulation in the A1FI_c000 scenario, the negative influence by the weakened THC causes the stock to decline to about 1 million tons in the A1FI_c090 scenario (Fig. 6-5). In the other two scenarios, the stock biomass remains stable throughout the simulation period. There is an increase in variability of stock size but that effect is only marginal.

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. 6-5). 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. 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.

Cod catches show a similar pattern with profit-maximizing harvesting as with adaptive harvesting, but overall average catch sizes are somewhat lower (Fig. 6-6). 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. Consequently, the stock sizes are generally higher with profit-maximizing harvesting and catches are lower. Catch levels of coastal vessels are similar for both harvesting strategies, while the difference in landings is mainly attributable to reduced trawl catches. The importance of the coastal vessels in the cod fishery is therefore distinctly greater in a profit-maximizing fishery than in an adaptive fishery.

Average annual capelin catches are similar in three of the four scenarios, with landings amounting to 200 000 to 300 000 tons per year throughout the simulation period. Only in the A1FI_c090 scenario, the capelin fishery can benefit from the generally larger stock size. At the end of the simulation period, catches are more than twice as large as at the beginning of the century (Fig. 6-6). In all scenarios, capelin catches are substantially higher with a profit-maximizing harvest strategy, as the fishery has to deal with closures of the fishery due to a dangerously low stock size much less frequently than with an adaptive harvesting strategy. This has a positive influence on the profitability of the capelin fishery in all scenarios.

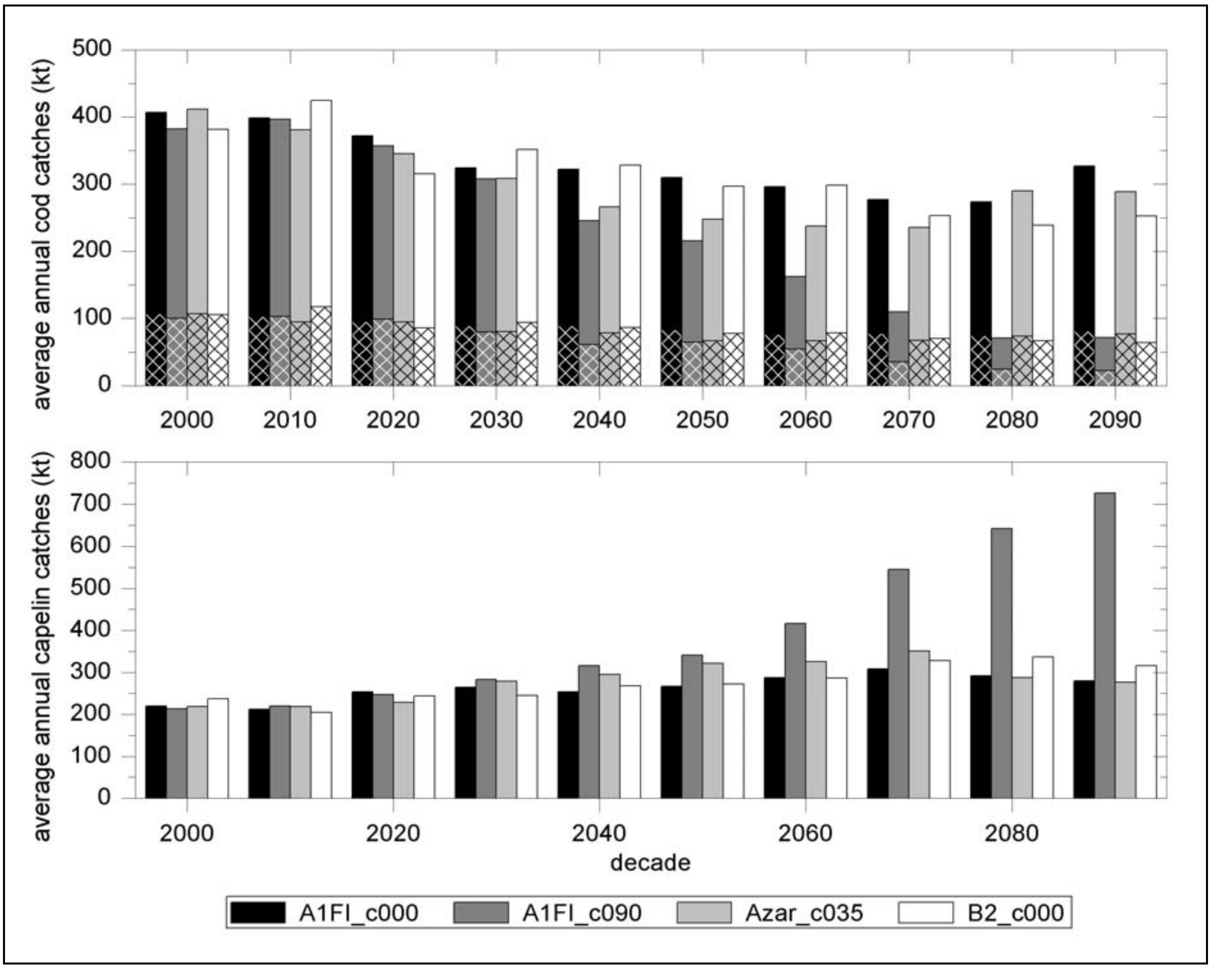

Figure 6-6: Average annual catches of all fleets in each decade if profit maximization is used. Cod catches: regular columns denote trawl catches, shaded columns catches by coastal vessels.

Compared to adaptive harvesting, profits from fishing are distributed quite differently among fleets when profit-maximizing strategies are used by the fishermen. Except for the A1FI_c090 scenario, in which the cod fishery becomes negative for both fleets in the last few decades of the simulation period, the average annual profits of all fleets are positive throughout the 21st century (Tab. 6-2). With profit maximization, profits are spread more evenly among trawlers and coastal vessels, causing the coastal vessel fleet to shrink much less than with adaptive harvesting. On the other hand, the number of trawlers stays more or less the same 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 with profit maximization than with adaptive harvesting, which reduces the operational risks of the fishery. Because of the higher number of fishing periods without a suspension of the fishery, the capelin fishery increases in size in all scenarios while remaining profitable in all decades. Despite the expansion of the fishery, its economic importance remains far behind the cod fishery.

	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	984.83	58	873.46	58	1009.54	58	832.21	58
2010s	966.65	57	947.15	57	903.85	57	1041.39	57
2020s	840.29	56	728.93	56	682.40	56	557.33	56
2030s	583.74	56	549.79	55	543.22	55	735.73	55
2040s	585.38	55	289.39	54	303.37	54	651.01	54
2050s	560.70	54	95.23	53	279.46	53	523.35	53
2060s	523.61	53	-161.87	52	224.25	52	530.51	53
2070s	408.04	52	-361.28	51	219.12	52	297.24	52
2080s	427.59	52	-527.11	50	544.60	51	239.48	51
2090s	736.49	51	-513.04	50	513.68	51	352.23	51
coastal vessels								
2000s	327.62	479	294.15	477	329.37	478	320.03	477
2010s	311.27	468	310.87	467	262.26	467	398.47	467
2020s	265.55	458	291.76	456	264.86	457	210.37	458
2030s	228.60	448	173.27	447	179.97	447	264.20	448
2040s	237.86	439	70.63	436	170.02	438	217.10	438
2050s	211.90	430	94.74	423	106.88	429	173.14	429
2060s	170.00	421	34.71	413	110.23	419	182.62	419
2070s	189.72	411	-74.99	400	115.22	409	134.30	409
2080s	174.20	401	-133.91	386	170.28	399	119.43	401
2090s	227.72	389	-132.68	370	192.95	391	109.20	392
purse seiners								
2000s	76.07	73	73.75	73	77.42	72	85.94	72
2010s	71.66	74	77.28	74	77.27	74	68.17	74
2020s	94.48	76	92.48	76	81.87	75	89.42	76
2030s	101.07	78	111.39	77	109.90	76	89.73	78
2040s	94.74	80	128.99	79	117.82	78	102.77	79
2050s	101.06	82	144.37	81	131.80	81	103.82	81
2060s	112.40	84	187.75	83	133.25	83	111.26	83
2070s	123.75	85	263.38	84	147.31	85	133.34	85
2080s	115.85	86	320.00	86	109.77	87	137.30	88
2090s	108.76	86	368.42	89	103.13	88	125.64	91

Table 6-2: Average annual profits and fleet sizes in each decade if a profit-maximizing 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.

6.5 Discussion and conclusions

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.*, 2005). 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 on average is 40% (adaptive harvesting) to 65% (profit maximization) smaller in the scenario with a THC weakening. 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.

Chances of successful capelin recruitment also increase with warmer spawning conditions, which is beneficial for stock development. However, warmer conditions in the Barents Sea also increase the probability of young herring migrating to the Barents Sea to feed on capelin larvae. 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 frequently, which is the case in the scenarios with adaptive harvesting of the stock. In the profit maximization simulations, the capelin stock is on average 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 of warming without the THC breaking down. The cod fishery remains viable despite increased natural variability in the two other 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 adaptive harvesting strategy clearly favors the trawl fleet while catches by coastal vessels are too small to profitably operate the fleet. Consequence is a clear reduction in fleet size while there is a simultaneous expansion of the trawl fleet. In contrast, coastal vessels remain a vital part of the cod fishery under profit maximization. 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 considered in these simulations, the profit-maximizing harvesting strategy leads to much more stability in the cod fishery than the adaptive strategy.

Capelin catches are similar in all scenarios during the first half of the simulation period, when any hydrographic change is still small. In later fishing periods, the capelin fishery can benefit from warming, as recruitment success of the stock improves. The largest amounts of capelin are landed in the A1FI_c090 scenario, in which the capelin fishery can harvest the additional capelin that does not fall prey to cod due to the reduced number of predators left which helps the capelin fishery gain the highest returns regardless of the harvest strategy employed. The main difference between the two strategies is the large number of fishing periods in which the fishery needs to be closed due to low capelin abundance, if fishermen follow an adaptive strategy. If the stock is exploited with this harvest strategy, it can barely recover above the threshold biomass level of 1 million tons before harvest activities drive down the stock size again. This explains the average capelin stock size of approximately that biomass level. The fixed costs of maintaining the fleet in idle times reduce the profitability and therefore diminish the economic importance of the capelin fishery. Only when the population dynamics improve considerably due to warming, adaptive harvesting leads to distinctly positive returns from harvesting capelin.

Overall profits from fishing are initially higher with adaptive harvesting strategies than with profit maximization, even though the large returns only stem from the trawl fishery, while coastal vessels and the purse seine fishery of capelin operate below or close to their respective break even points. It can hardly be desirable to have one part of the fishery system practically subsidize the other fleets. Profits from profit-maximizing 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), total profits of all fleets exceed those accrued with adaptive harvesting. Also, a profit-maximizing strategy with a longer optimization period yields superior results than a short-term profit-maximization as harvesting is greater during the first decades of the simulation period, if profits are maximized for the present fishing period only. This causes 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 Arcto-Norwegian 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 and the technological state of the fleets do not change in the simulations. As climate change progresses, technological advances have to be made and/or fishing strategies adjusted to maintain operation of the fisheries. Increase in harvesting efficiency to reduce costs, shifts of fishing effort to other species and/or supplementation of high seas landings by fish production in aquaculture are options to improve the profitability of the fishing industry in times of uncertain stock development arising from changes in circulation patterns and subsequent environmental changes in the marine habitats.

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 fisheries under adaptive and profit-maximizing harvesting strategies. 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.

7 Conclusion

7.1 Summary of results

A strong decline in strength of the Atlantic thermohaline circulation as a consequence of anthropogenic climate change will have a wide range of impacts, not only on the physical environment of the affected regions but also on biodiversity, ecosystem stability, economic activities, water resources, and human energy consumption. In order to be able to deal with the consequences of a weaker THC appropriately, it is important to know which regions and societal sectors will be most affected, and how large possible damages will turn out to be.

In this thesis, one focus is on the overall socioeconomic impacts of a possible THC breakdown. They are assessed by applying and extending the integrated assessment model *FUND*. The spatial resolution of the model is improved to distinguish individual countries rather than regions because the characteristics of the impacts of a THC weakening generally vary more on a national or subnational rather than regional scale. Climate impact scenarios stemming from reductions in THC strength were adapted from grid-based GCMs and applied as external forcing in the model simulations.

In chapter 2, an initial assessment of the socioeconomic consequences of a THC shutdown was conducted with *FUND 2.8* using scenario data generated by the *CLIMBER-2* model (Rahmstorf & Ganopolski, 1999). Two cases are compared, one in which the THC weakens by less than a third by 2150 and even recovers to some extent by 2300, leading to an increase in winter air temperature over the North Atlantic of 4°K by the second half of the 22nd century. In the other scenario the THC declines to almost zero by the beginning of the 23rd century and does not recover. This causes a strong temperature drop in the middle of the 22nd century and the North Atlantic actually ends up 3°K cooler at the end of the simulation period.

The results show that the consequences for the North Atlantic region are less pronounced when occurring in the context of global warming than if the THC shutdown had occurred without the background of anthropogenic climate change. The reason is that the cooling of the North Atlantic following the reduced heat transport by the ocean circulation offsets global warming to some extent, thus reducing the climate change induced damages in the adjacent regions. Furthermore, the shutdown takes place over several decades, which is a fairly long time scale from the human perspective. But despite the reduction in damages, the overall and marginal impacts of climate change remain negative regardless of the fate of the THC. However, total damages incurred from climate change amount to only a few per cent of GDP in the regions most affected by a THC breakdown.

It has to be noted that the model setup misses some important features regarding economic activities and ecosystems. Furthermore, the geographical resolution of only 16 main world regions is too crude to allow the results to be more than qualitative, as the aggregation of climate change impacts to a regional level removes some key characteristics, particularly in the areas most affected by a THC shutdown. These issues are addressed in subsequent model development to improve the prognostic capabilities of the model.

The analyses of a THC shutdown scenario in chapter 3 using *FUND 2.8n* is a more sophisticated approach in estimating the impacts of changes in THC strength, as socioeconomic impacts are estimated on a national level for 207 individual countries. The assessment is driven by a scenario that is derived from the integrated THC analysis conducted with the *HadCM3* model (Vellinga & Wood, 2002), in which a fresh water pulse is added to the North Atlantic to artificially stop the THC. Medium term impacts on temperature and precipitation are superimposed on the *FUND* scenario of climate change (Tol, 1999a), in which it is assumed that the THC weakens during the second half of the 21st century and stops by the year 2100.

The resolution of individual countries allows the distinction of eight different response patterns to weakening of the THC. The first four relate to absolute warming or cooling. In some countries, e.g. in Gambia, the global warming trend is amplified by a reduction in THC strength; climate change damages increase, thus a THC slowdown is negative. In contrast, in countries like Australia or New Zealand, in which warming is actually beneficial, additional warming brought about by a THC breakdown would have an overall positive impact. There are also countries that already experience slight cooling without a THC change, that would experience further cooling in case of a THC shutdown. E.g., in Iceland, this cooling is negative and the situation would worsen if the THC weakened. On the other hand, the Caribbean would benefit from cooling and an amplification of that trend is a positive development.

Furthermore, there are relative changes in warming or cooling trends caused by a weaker THC. In countries like Egypt, the warming trend, which is generally negative, is offset to some extent when the THC slows. This reduces damages, so a THC change has a positive influence. The situation is different in countries such as France or Spain, where this offsetting effect actually adds to the negative socioeconomic impacts, mainly by reducing positive developments of non-market impacts of climate change. Also, countries may first benefit from climate change but THC weakening diminishes these benefits. Such is the case in Iraq. An even more pronounced trend can be observed in e.g. Denmark, where a weaker THC actually reverses the initially beneficial effect of global warming. The named countries are representative for each category in the response pattern and all other countries can be fitted in one of them. Most countries experience relative cooling, thus an offsetting effect of the THC breakdown on the background warming. Socioeconomic impacts are in most cases limited to a few per cent of GDP but in some countries, the extra damages incurred by a weakening of the THC turn out to be considerable.

The most important economic sectors affected by an altered THC strength are water resources and energy consumption. The widespread changes in temperature and precipitation following a THC shutdown cause heating to become more important in areas that are cooled. Also, shifts in precipitation patterns can increase the scarcity of water, therefore increasing the costs for securing the supply of adequate amounts of water for human consumption and industrial use. Among health related impacts, the changes in the spread of cardiovascular and respiratory diseases are of particular importance as heat or cold related stress increases as a consequence of the additional temperature effect of the THC shutdown.

Even though it has to be noted that the estimate of damages from a THC shutdown is only 0.1% of global GDP, there is a negative impact on welfare. But these impacts are not evenly distributed and there are many countries with little economic power that are more confronted with the indirect effects of THC weakening than other more developed countries. Overall, based on all information gained in these assessments and given its low probability of occurrence, a shutdown of the THC is not an event that currently requires drastic action to deal with the possible impacts. This does not mean that the consequences of anthropogenic climate change are to be taken lightly. On the contrary, the implications of global warming can be expected to be detrimental in many parts of the world. Nevertheless, the additional damages arising from a THC breakdown in a scenario of global warming turn out to be more marginal.

Based on the results of the analyses with *FUND*, which indicate that socioeconomic impacts of a THC breakdown are not only heterogeneously distributed geographically but also with regard to economic sectors, the second part of this thesis focuses on the fisheries of Arcto-Norwegian cod and capelin in the Barents Sea. These fisheries contribute considerably to the GDP of the countries exploiting these stocks and are directly confronted with the environmental changes caused by a shutdown of the Atlantic THC.

In chapter 4, the economic impacts of changes in THC strength on these fisheries are explored using a bioeconomic simulation model of the two species and their associated fisheries. In this assessment of the fate of the fisheries over a 100-year simulation period, the fishermen follow an adaptive harvesting strategy. This strategy is based on a comparison of actual catches in a fishing period with a previously determined target catch size. Fishing effort in the subsequent fishing period is adjusted depending on whether actual landings were smaller or greater than the target catch size. A shutdown of the THC is represented by a sudden reduction of the environmental carrying capacities or productivities of the species at the midpoint of the simulation, with the key quantities governing population dynamics remaining at the altered level for the remainder of the simulation period.

The simulations show that in the long run reduced productivity or carrying capacities lead to lower stock sizes and consequently to smaller catches. During the first few years after the change in population dynamics the fisheries are hardly affected as profits remain practically the same as in the reference scenario with unaltered population dynamics. Even though catches do slightly decline, the net present values of profits change only little because of discounting. Two decades after the change in population dynamics, the economic consequences are clearly visible, as annual catches are markedly lower than in the reference scenario and profits have dropped considerably. For large changes in productivity or carrying capacity, the cod fishery becomes completely unprofitable. The reductions in economic success is much less pronounced for the capelin fishery than for the cod fishery, as the capelin stock can benefit to some extent by a smaller predator stock size of cod. The release in predation pressure allows extra capelin to be harvested, which helps stabilize the returns from fishing of the capelin fishery. In some scenarios of carrying capacity change, there is a tendency to maintain landings at a high level after the change in population dynamics by increasing fishing effort. This has the effect that the short term economic result remains stable, but the subsequent negative development of the fisheries is amplified by such short-sighted behavior.

Sensitivity analyses of the average market price of capelin, the discount rate, and the learning factor of the fishermen illustrate that a higher capelin price owing to a larger share devoted to human consumption is extremely beneficial to the fishery. As the generally high fishing effort applied leaves little room for expansion of the fishery, higher revenues directly translate to a higher profitability of the fishery. An analysis of the applied discount rate demonstrates that for the cod fishery, a medium discount rate yields the best economic results, whereas very low or high discount rates lead to worse overall profits. For the capelin fishery the trend is different, as net present values of profits increase with the discount rate, owing to the large interannual variability in the fishery.

The speed in which new information on stock development is incorporated into the calculation of the target catch size also has a profound economic impact. Even within the cod fishery there are fleet-dependent differences; e.g., coastal vessels that harvest mainly older age classes should rely mainly on long-term information of stock development, while trawlers that target younger age classes than coastal vessels should utilize a larger share of short-term information in order to optimally apply the adaptive harvesting strategy.

The bioeconomic model is further extended in chapter 5 to allow vessels to enter the fisheries in very profitable periods or to exit if the fishery has become unprofitable. Furthermore, management measures by means of TACs were incorporated, an important feature in the assessment if profit-maximizing harvesting strategies are utilized by the fisheries to prevent a complete depletion of the stocks at the beginning of the simulations. The same scenarios of changes in population dynamics were applied to the improved model version and simulations conducted with fisheries using profit-maximizing harvesting strategies with various optimization periods.

Results show that the distribution of fishing effort within the cod fishery changes depending on the length of the optimization period. For a very short time horizon of optimization, almost all cod is caught by the trawl fleet, which has a higher catch efficiency than the coastal vessels. Landings and net present values of profits are highest with this harvesting strategy, but the pressure on the stocks is considerably high and even a small change in stock dynamics has negative economic implications. If profits are optimized over several fishing periods, fishing activities may be deferred in order to allow the stocks to grow and to increase future landings. In this case, the smaller and less cost-intensive coastal vessels are of greater importance in the cod fishery, as they incur fewer losses in periods in which harvest activities are ceased.

Looking at the impact of changes in population dynamics, a small change in either productivity or the carrying capacity has only little economic impact. Generally, profitability can be maintained at a level close to the returns from fishing in the reference scenario. A strong reduction in either quantity, however, has a lasting impact on long-term stock development. This leads to lower overall catch sizes and consequently to lower income from fishing. Here, the decline in economic activity is particularly significant for the cod fishery not only due to the higher value of the fish but also because of the much higher amount of capital investments in the operation of the cod fishery. Generally, a lower productivity has a more profound economic impact than a lower carrying capacity, since both stock sizes are currently far below their actual carrying capacities. Thus a reduction of this quantity has initially little impact on stock development. In order to observe a lasting impact on the stocks that translates into lower annual catches, it is necessary to significantly lower the carrying capacities.

Sensitivity analyses of the average market price of capelin and the discount rate applied confirm that an increase of the capelin price leads to an increase of the profitability of the capelin fishery that is similar to the one observed for the adaptive harvesting strategy. While the fishing effort of the vessels involved in harvesting capelin is quite high throughout the simulation period, the increased profits lead to an expansion of the fleet, as new vessels enter the fishery. The effect of larger profits as a consequence of higher capelin prices is largest in the early years of the simulations and diminishes over time. The discount rate influences the optimization result in each fishing period and thus has a distinct impact on the optimal harvesting strategy. Whereas the strong reliance on trawlers for short optimization periods is independent of the discount rate used, the best economic results are obtained for medium discount rates with an optimization period of 5 years. For a very long optimization period, high profits can be obtained with any discount rate, as stock dynamics become the most important factor in determining economic success.

The bioeconomic model is linked to scenarios of THC change generated by the *CLIMBER-3α* model in chapter 6. Four scenarios are analyzed. These scenarios show different degrees of reduction in THC strength as a consequence of anthropogenic climate change, depending on the global warming scenario and the additional freshwater flux applied (Kuhlbrodt *et al.*, 2006). For each scenario, the economic development of the Barents Sea fisheries during the 21st century is determined using both harvesting strategies described in the previous chapters.

The simulations reveal that there are two opposing effects influencing the development of the fish stocks: Global warming is generally beneficial for the stocks as the probability for strong recruitment year classes increases with water temperature at time of spawning; on the other hand, survival rates of young age classes of cod diminish as the THC weakens. This happens because more cod larvae end up West of Svalbard on their Northward drift from the spawning grounds, away from their feeding grounds, once the THC is reduced. Consequently, the development of cod is worst in the scenario with the largest change in THC strength, while the capelin stock can actually benefit considerably from the reduced predation pressure in that scenario.

The fisheries are generally positively affected by global warming, as recruitment success improves with warmer conditions in the region of spawning, causing the standing stock biomass to increase. Harvest activities are expanded, which leads to an expansion of the trawl fleet under adaptive harvesting at the cost of coastal vessels, whereas fleet sizes remain more stable with profit-maximizing harvesting. The capelin fishery suffers from many periods of temporary closures with adaptive harvesting strategies. Only under profit maximization, the stock biomass is kept at a level sufficient to prevent frequent closures of the fishery. If the THC breaks down, the cod fishery becomes unprofitable in the second half of the 21st century regardless of the harvest strategy chosen. In contrast, the capelin stock biomass expands particularly strongly in this scenario, creating the highest economic success of the capelin fishery in all scenarios. However, this expansion of the capelin fishery is by no means large enough to compensate for the losses incurred by the concurrent breakdown of the cod fishery.

A comparison of the harvesting strategies illustrates that in the early years of the simulation the adaptive strategy yields higher profits than the profit-maximizing strategy. However, when the overall variability of stock development increases over time as a consequence of climate change, profit maximization turns out to be the more successful fishing strategy in the long run. In general, profit maximization over several fishing periods leads to higher returns from fishing than a shorter optimization period, as the stocks are allowed to maintain higher standing biomasses. This increases the stability of the stocks, which is particularly important if uncertainties in population dynamics increase as a consequence of changes in environmental conditions.

7.2 Relevance of the thesis

The analyses in this thesis contribute to the research field of climate change impact assessment as existing methods of assessment of socioeconomic impacts of climate change were extended to analyze the consequences of specific scenarios of a THC shutdown. The methodological advances were conducted with two different types of models in order to obtain insights not only about the general impacts of a THC collapse but also on the consequences for a particular economic sector.

In contrast to previous IAM assessments of a collapse of the THC in which the consequences of a THC breakdown were parameterized as additional climate change related damages (Mastrandrea & Schneider, 2001) or where the THC shuts down abruptly if a threshold level of greenhouse gas concentrations has been reached (Keller *et al.*, 2004), the analyses in this thesis consider the trajectories of THC strength over time to capture the socioeconomic impacts that already occur if the THC weakens but has not collapsed completely as well. This approach recognizes that a possible THC shutdown does not just happen but manifests itself over some decades in which the overturning weakens progressively and that the rate of weakening influences the extent of socioeconomic damages. Furthermore, it does not ignore that the THC collapse takes place concurrently with a general global warming trend, since damages attributable to a THC breakdown differ considerably depending on the background climate change scenario applied.

It was possible to demonstrate that the extent of damages following a THC shutdown taking place over a period of 30 years is not large enough to be catastrophic on a global scale. Based on only these results, it would not be necessary to increase measures of greenhouse gas emission reduction to explicitly save the THC. However, this does not mean that it is possible to loosen up on efforts to reduce greenhouse gas emissions simply because the THC breakdown is unlikely to be devastating. Even without a collapse of the THC the overall consequences of the background warming trend will be disastrous if mitigation and adaptation measures remain inadequate.

The increase in spatial resolution of the IAM used allowed the categorization of the overall socioeconomic impacts of a THC shutdown on a national scale. This is especially important as these consequences are heterogeneously distributed geographically and extend over the whole globe, while the direct climatological and hydrographic consequences of a reduced overturning are generally considered to be confined to mainly the North Atlantic region. The assessment results may therefore increase the awareness that socioeconomic impacts of climate change are usually a global burden, even though they are triggered by regional or local change in environmental conditions.

The second part of the thesis with its focus on the Barents Sea fisheries addresses issues that are also interesting from the perspective of fisheries management, as concrete guardrails for the exploitation of marine resources are generally determined on the basis of virtual population analyses and applications of bioeconomic models. Conventional bioeconomic models, however, cover only short simulation periods, in which environmental conditions are considered to be constant, and it is therefore not possible to account for trends in stock dynamics that are attributable to climate change. Consequently, management strategies based solely on such short-term models disregard the influence that long-term shifts in fish stock development may have even over fairly short periods of time. Yet, the biological implications of climate change and altered circulation patterns are substantial and are therefore likely to have a lasting impact on the fisheries that should be addressed by decision makers.

This extended bioeconomic simulation model is the first to combine the vastly different time scales of economic and hydrographic processes dynamically in the same model and to account for the impacts from environmental change in addition to economic exploitation and natural variability when determining the actual development of the stocks considered. The assessment results indicate that determining harvesting strategies without regard to trends in population dynamics has a negative influence on the long-term economic success of the fisheries. Because of the large amount of capital invested in the marine fisheries in the North Atlantic, it is necessary to consider variable environmental conditions when devising a long-term management strategy so that reductions in returns from fishing can be dealt with appropriately by adjusting fishing effort and fleet sizes to maintain the profitability of the fisheries at an acceptable level without risking their collapse.

7.3 Possibilities for further research

Simulation models are generally an essential tool for researchers and decision makers to determine the possible effects of changing environmental conditions on the success of management strategies, in order to adapt to the new situation early and to minimize adverse impacts. But because reality is always too complex to be completely described by a model, simplifications are necessary so that the reliability of the model results remain tentative to some extent.

This also holds true for the models used in this thesis: Even though it was possible to include many important economic processes and climate feedbacks to make interesting inferences on the basis of the assessments of THC change, the current model version is not perfect when it comes to describing the economic impacts of a weakening of the THC. Therefore, further extensions of the model are needed to improve the predictive quality of the simulation results.

One aspect that is not yet endogenously represented in *FUND* is the general ocean circulation that is important particularly in the context of altered circulation patterns. Current simulations have applied temperature and precipitation patterns arising from externally generated scenarios of THC change. Therefore, possible feedbacks between economic activity and the driving forces of the THC are disregarded. Internalizing the main ocean dynamics can improve the quality of the scenario analyses, as adaptation or mitigation efforts may have an influence on the extent of THC weakening – an effect that is impossible to observe if dynamic feedbacks with the ocean circulation are not implemented.

Because the THC change scenarios in the assessments are externally derived and cannot be dynamically influenced during the simulations, the obtained results depend considerably on the trajectory of THC development. It seems therefore reasonable to repeat the analysis with the *FUND* model using scenarios from other GCMs to check the robustness of the results obtained in this thesis and to determine the extent to which IAM assessments of circulation changes depend on the chosen scenarios.

Even though *FUND* covers a wide range of economic sectors that describe the general economic characteristics in all 207 countries distinguished in the model, some economic sectors such as fisheries or tourism, which are of importance in only a few countries but are expected to be distinctly influenced by a reduction in THC strength, are not yet considered separately (cf. chapter 3). The higher uncertainties involved in the management of marine resources caused by altered circulation patterns are likely to have a negative effect on welfare in countries in which fisheries play an important economic role. A similar argument can be made for tourism, as temperature and precipitation patterns, which may change significantly in case of a THC shutdown, greatly influence the attractiveness of travel destinations. Including these economic sectors individually in *FUND* would help to create a more differentiated picture of the socioeconomic consequences of changes in THC strength.

While global scale IAM assessments can only consider the most important economic sectors, processes and feedbacks with climate development, models of individual economic sectors that focus on a limited geographic region, such as the bioeconomic fisheries model applied in this thesis, are supposed to provide a more detailed and accurate description of economic activities and their development for given boundary conditions. The model developed for the analyses in this thesis already encompasses many important aspects of the Arcto-Norwegian cod and capelin fisheries. However, it seems reasonable to add some additional components to the model in order to obtain a more accurate view on the development of the fisheries, as these processes may greatly influence the fate of the high seas fisheries in times of rapidly changing environmental conditions.

There is a whole range of components that could be added to the present model to improve its predictive capabilities. First of all, different food sources of the fish species other than predation or cannibalism should be considered, particularly the plankton availability for capelin, as survival rates can be vastly reduced if food is too scarce to support the given stock size. Since not only the amount of food available but also the overlap between the species and their food sources is important, a useful extension of the model would be the addition of a spatial component. The inclusion of geographic references is also significant for the fisheries, as the species' ranges change with environmental conditions and fishermen have to adapt their fishing grounds to the areas where the fish are present. This creates variability in fishing costs due to shifts in distances between ports and fishing grounds.

Furthermore, it is assumed that fishing activities continue with current technological understanding because technological change is hard to model as it does not occur steadily and is hardly predictable. It has, however, a profound impact on the development of the fisheries and would therefore be a worthwhile model extension, as shifts in harvesting efficiency help to reduce costs while increasing catches per unit effort, which would boost the profitability of the fleets.

Finally, as the operation of high seas fisheries becomes more difficult, fish from aquaculture is a substitute product that already grows in importance. Aquaculture is an additional competitor for the marine fisheries, providing an additional market pressure. Since aquaculture is less influenced by changes in environmental conditions than the high seas fisheries, they may become a determining factor the fate of the marine fisheries in times of large environmental variability. Therefore, aquaculture should be considered in long-term bioeconomic fisheries models.

Despite the limitations in the setup of the simulation models used in this thesis, the results already provide useful insights into the extent of possible impacts of a shutdown of the Atlantic THC. It is a first step towards estimating the economic risk arising from THC weakening, not only for the entire economy of a country but also for individual economic sectors, in this case key fisheries in the Nordic Seas. The possibilities of a further development of the applied simulation models linking socioeconomic impacts of climate change to the physical processes are plenty, as shown above. Including only a few of them may already increase the value of the models as tools for devising strategies to successfully deal with the often adverse consequences of anthropogenic climate change.

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ISSN 1614-1199