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CLIMATE CHANGE AND EUROPEAN FISHERIES

FISHERIES

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Directorate General Internal Policies of the Union

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FISHERIES

Climate Change and European Fisheries

STUDY

Content:

Climate change is expected to result in several processes that can have an impact on the biological productivity of the marine ecosystems and on the distribution of marine resources.

The purpose of the present study is to provide an analysis of the probable impacts and consequences of climate change on European Union marine fisheries and aquaculture. The basis of the study is a comprehensive review of approximately 200 relevant and up-to-date scientific literatures with particular reference to the fisheries resources that are relevant for the European Union fisheries both in the Atlantic and in the adjacent seas (Mediterranean, North Sea and Baltic).

The effects of climate change on fisheries will affect a sector already characterised by full utilisation of resources. Changes in the productivity of the ecosystem will have a profound effect on the sustainability of the fisheries. Because of that; climate change is currently the target of very extensive research for estimating how fish stocks will develop in the future and other issues having a significant impact on European Fisheries.

Seven possible policy options have been identified and are discussed in the study.

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Executive summary

Background and Objectives

Climate change is expected to result in several processes that can have an impact on the biological productivity of the marine ecosystems and on the distribution of marine resources.

The effects of climate change on fisheries will affect a sector that is already characterised by full utilisation of resources. Changes in the productivity of the ecosystem will have a profound effect on the sustainability of the fisheries. Climate change is currently the target of very extensive research. The related knowledge is important for estimating how fish stocks will develop in the future.

Against this background the purpose of the present study is to provide an analysis of the probable impacts and consequences of climate change on European Union marine fisheries and aquaculture. The basis of the study is a comprehensive review of the existing literature with particular reference to the fisheries resources that are relevant for the European Union fisheries both in the Atlantic and in the adjacent seas (Mediterranean, North Sea and Baltic).

The study includes a conceptual framework describing the key processes driving the dynamics of the ecosystems and the fisheries resources. The framework has been used to systematically review the literature of the effects of climate change on the key species relevant for the European Union fisheries.

Literature review

A literature review of approximately 200 relevant and up-to-date scientific literature citations and relevant studies has been carried out from January to May 2007. On the basis of the findings from the literature review a number of 40 climate change driven phenomena related to specific trends and effects have been identified (see Table 2). For each phenomenon a degree of confidence has been attributed on the basis of the reliability of the literature sources and the frequency of similar findings.

Conclusions and recommendations

- **Greenhouse gases contribute to climate change and are a threat for industrial fishing**

Man-made greenhouse gases continue to rise and contribute in a large proportion to climate change and changes of the marine ecosystem. Greenhouse gases are a threat for the already weakened fish stocks and their releases should be minimised.

- **Properties of water are already changing**

It is scientific consensus that climate change is reality. ***Temperatures will increase and sea level will rise***. Warming of the climate system has been detected in changes of surface and atmospheric temperatures, temperatures in the upper several hundred metres of the ocean and in contributions to sea level rise. Average global temperatures have increased by ~0.6°C and sea level has risen 0.17m over the past century. During this period, both marine and freshwater systems have warmed. The coastal marine climate of Europe is predicted to continue to warm throughout the 21st century, with the forecast for the sea surface temperature to increase by 0.2°C per decade. ***Model estimates predict ocean acidification([1])***. The pH reduction in the ocean surface range from 0.3 to 0.5 units over the next 100 years and from 0.3 to 1.4 units over the next 300 years. *Salinity will change*. In the nordic seas and the Baltic decreases in salinity([2]) are expected whereas in the Mediterranean salinity is expected to increase.

The Atlantic thermohaline circulation([3]) will be weakened. The water bodies of the North Sea and Arctic regions interact by exchange of cold and warm water flows. They are driven by the Atlantic thermohaline circulation. The flow intensity is influenced by climate change. Currently the flow intensity may already be reduced by 30%. It is unlikely that the circulation will shut down completely which would have strong impacts on current patterns (e.g. a short term sea level rise in the North Sea of 1m, a long term global sea level rise of 0.5m, a southward shift of the tropical precipitation([4]) belt and a reduction of biomass in the Atlantic by 50%).

Stratification will increase([5]). It has been demonstrated, that climate change causes increased stratification of the Baltic Sea, the North Sea and the Mediterranean Sea. Stratification of the water column leads to natural barriers where organisms can concentrate or where organisms have to pass through. Stratification increases with increasing salinity and temperature. Increased stratification hinders mixing with deep water and causes reduced replenishment of nutrients.

Changed circulation and stratification will change the geographical distribution of organisms. Currents play an important role in transporting organisms like plankton([6]) and fish over large distances and can thus increase their distribution range. On the other hand, currents also act as a biogeographical barrier([7]) between the water masses on both sides of a current. They reduce the exchange of organisms across the current. Warming may lead to weakening of alongshore currents, thus decreasing the distribution with the alongshore current, but breaking down the barrier between coastal and offshore water. This may lead to range extension of organisms previously trapped near the coast. All these effects impact (positively or negatively) on primary production([8]).

Climate change impacts may be even more severe in semi-enclosed seas than in the open seas. Expected impacts will have negative and positive effects on marine productivity. According to climate change scenarios for

- the Baltic Sea the prognosis for a decrease of salinity ranges from 8% to 50% and for the increase of the sea surface water from 2 to 4°C.

([1]) Decrease of the pH; the pH is a measure of the acidity or alkalinity of a solution.
([2]) The relative concentration of salts, usually sodium chloride, in a given soil or water. Freshening in this context refers to a decrease of salts in the water. Unitless; sometimes the old unit psu (practical salinity unit) is still used.
([3]) Circulation in the ocean that is driven by the density differences caused by temperature and salinity differences.
([4]) Meterology: the falling products of condensation in the atmosphere, such as rain, hail or snow.
([5]) The occurrence of more or less horizontal water layers in the sea as a consequence of differences in density, i.e. salinity (halocline) or temperature (thermocline).
([6]) Floating organisms whose movements are more or less dependent on currents. While some zoo-plankton exhibit active swimming movements that aid in maintaining vertical position, plankton as a whole is unable to move against appreciable currents.
([7]) Change in the environment, that hinders an organisms to spread further.
([8]) Assimilation (gross) or accumulation (net) of energy and nutrients by green plants and by organisms that use inorganic compounds as food.

- the North Sea region, the prognosis for salinity is variable with expected increases and decreases in different areas of the North Sea. The sea surface temperatures are predicted to rise about 1.6°C to 3.0°C in the northern North Sea and 3.0°C to 3.9°C in the shallower southern North Sea.
- the Mediterranean Sea salinity and temperatures will increase.

- **The North Atlantic Oscillation**

The North Atlantic Oscillation impacts on the European marine ecosystem. Many aspects of the winter climate in the European area are strongly influenced by the "North Atlantic Oscillation" (NAO)([9]) which dominates the atmospheric behaviour in the North Atlantic. Several indices for the NAO have been defined. The NAO affects all marine trophic levels([10]). Recruitment([11]) of industrial fish is linked to the NAO index as demonstrated for the gadoid([12]) outburst (concerning cod, haddock, whiting and saithe) in the North Sea and for herring and sardine recruitment in the Northeast Atlantic. The NAO is highly unpredictable, although it is possible to reconstruct the NAO from sea surface temperature.

The analyses of the NAO index and the relation to observed impacts on the marine ecosystem may enable to develop models for the prognosis of future impacts.

- **Effects on industrial key fish species have been observed in many cases**

Changes in temperature can lead to shifts of fish populations, the invasion of alien species and disappearance of species. Temperature is a fundamental component of the niche of fish. Fish tend to select thermal habitats that maximise their growth rate. However, predicting the effects of temperature change on fish is difficult. In addition to temperature, food availability and suitable spawning grounds determine the large scale distribution of fish. Direct and indirect climate effects can lead to a shift of fish populations, the invasion of alien species and even to the disappearance of species. In several studies the abundance and distribution of fish and zooplankton([13]) related to a rise in sea temperature was observed.

Warm fish species invade "cold" ecosystems. Several warm fish species have invaded "cold" ecosystems and cold species which used to be relatively abundant in "warm" ecosystems have become very scarce or have disappeared. E.g. sprat and mackerel have become very scarce or disappeared from the Mediterranean Sea. Shifts have been shown in many more cases. However, since the considered species are often heavily exploited, the establishment of direct causal relationships between temperature and distribution pattern is difficult. Reliable prognoses on the probable development of fish stocks due to climate change effects are only possible for some intensively investigated species (e.g. Atlantic cod). Separation from other impact factors is difficult. Research is needed.

([9]) The North Atlantic Oscillation is a dominant atmospheric behaviour in the North Atlantic; for explanation see chapter 3.1 – *Other relevant literature related to changes of properties of water.*
([10]) Classification of natural communities or organisms according to their place in the food chain. Green plants (producers) can be roughly distinguished form herbivores (consumers) and carnivores.
([11]) The number of fish added to the exploitable stock, in the fishing area, each year, through a process of growth (i.e. the fish grows to a size where it becomes catchable) or migration (i.e. the fish moves into the fishing area).
([12]) Group of fish species belonging to the family gadidae, e.g cod, haddock.
([13]) Planktonic animal.

Climate change influences abundance and distribution of industrial fish. Changing climate has a direct influence on survivorship, dispersal, fertility and behaviour of individuals and thus on abundance and distribution. Prognoses are difficult since many factors other than climate impacts play an important part in determining species distribution and the dynamics of these changes. Changes in the geographical range extension have contributed to an increased productivity of cod and haddock around Greenland. This has been a response to dramatic warming in 1920 to 1930. The primary cause for these changes were bottom up processes due to increased phyto- and zooplankton production.

Mean bottom temperatures can be crucial for the growth rate of a fish stock. According to simplistic simulations developed for the North Sea cod, increasing bottom temperatures are expected to have a negative impact on the growth rate of cod. Such approaches demonstrate that the inclusion of environmental factors in fish population models can alter the prognosis on how populations will behave. Simulations can provide management advice and show that the inclusion of environmental effects may become increasingly important in fish stock management.

As demonstrated by several examples, ***climate change can have an indirect positive or negative effect on reproduction success of industrial fish***. In the case of the Norwegian spring spawning herring a climatically driven increase in water temperature has the effect that fish populations do not participate in the usual spawning process. This has an indirect effect on the reproductive potential and directly impacts on commercial fisheries (loss of stocks). Blue fin tuna could also reproduce outside of its traditional spawning grounds during warm periods. This would have a positive effect on the productivity of the blue fin tuna stock.

Climate change causes shifts of industrial fish populations. Several examples for temperature or salinity induced changes of interactions (food organisms, predators, competitors, reproduction) result in the shift of populations. These examples can be used to explain some interactions and internal changes in ecosystems. However there is a need to conduct studies on population and community levels, since direct climatic effects on individuals do not translate directly into changes in distribution and abundance of fish populations.

Effects of climate change on plankton lead to the shift of fish populations. Many industrial fish species are directly plankton dependent. Plankton-feeding fish species, in particular sardine and anchovies, show strong natural fluctuations with climate variations. Investigations related to climatic warming indicated shifts from a dominance of northern species to a dominance of southern species. Shifts in boundaries using more than 60 different North Sea fish species showed a shift of boundaries of half of the species (exploited and non-exploited) with a northward trend. Some species may have reached their tolerance limits, such as cod in the North Sea, resulting in northwards movement of their populations. The decrease in cod was correlated with changed species assemblages, stock decline and smaller average body size of the zooplankton. This can probably be attributed to climate change. The shift of populations (e.g. as demonstrated for the Atlantic cod) can lead to the complete loss of stocks at the regional level.

- **Effects on the biological environment impact on industrial fish species**

Climate change impacts on prey and predators of industrial fish. Important organisms of the biotic([14]) environment of the industrial key fish species are their prey and their predators. For

([14]) Live and living organisms.

the planktivorous fish species the main prey organisms are small and large copepods([15]). For the Baltic Sea, small species like *Pseudocalanus* and *Acartia* are important food items, whereas in the North Sea and the North East Atlantic additional large copepods like *Calanus finmarchicus* and *C. helgolandicus* are important. Being important elements of the food web, their responses to climate impacts are crucial for the productivity of industrial fish stocks.

Invasive species are becoming more frequent in European coastal waters. Biological invasion has become one of the most prominent elements of global change. It can alter the biodiversity and functions of natural ecosystems and can cause significant economic damage.

Climate induced disturbance of the food web impacts on survival and productivity of industrial fish. For the survival and productivity of fish it is crucial that the abundance of fish larval stages matches together with the occurrence of the right sized zooplankton. Due to climatic changes many plankton taxa([16]) have been moving forward in their seasonal cycles. This leads to mismatches with severe implications on the survival and productivity of industrial fish stocks. If temperatures continue to rise, such disturbance of the marine food web will continue and will impact on the abundance and distribution of industrial fish. This has been demonstrated in many examples: Diatom blooms([17]) have negative impacts on diatom-dependent organisms in the North Sea. A mismatch in the size of the prey and the size of the cod cause reduced survival of Atlantic cod larvae. Reduced abundance of the prey of young sandeel leads to reduced survival of sandeel. Increased sea temperature causes reduced plaice and dab recruitment around the UK. A shift in the balance between meroplankton([18]) and holoplankton,([19]) and thus between benthos([20]) and pelagial, influences the survival of larval fish.

- **Economic implications for industrial fishery**

Climate change can have severe economic implications on industrial fishery. Assuming that industrial fishery is directly linked to marine production, an increase or decrease in productivity of 10% would result in an economic gain or loss of more than €200 million([21]). It is difficult to assess the impacts of shifts of fish stocks on industrial fishing because the shift related decrease is usually accompanied by a corresponding increase of another species.

Positive and negative economic impacts on industrial fishery are expected. It is not possible with the current state of knowledge to make quantitative predictions of changes in global marine production due to climate change because of the large numbers of interactions occurring. However it is clear that changes in productivity and seasonality will affect the exploitation of marine living resources. Estimations indicated (with a low level of confidence) that global marine production may increase but not more than 10% over the period until 2050. In contrast

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([15]) The largest class of crustaceans. Either free living or parasitic. Dominate the zooplankton but also occur with benthic species

([16]) A taxon is a group of organisms in biological systematic

([17]) When related to phytoplankton, a sudden and rapid increase in biomass of the plankton population. Seasonal blooms are essential for the aquatic system productivity. Sporadic plankton blooms can be toxic

([18]) Temporary plankton consisting of pelagic stages of organisms which also have benthic stages. Mainly larvae of sedentary organisms

([19]) Plankton with a completely pelagic life cycle

([20]) Organisms attached to or resting on the bottom or living on the bottom sediments

([21]) Based on an estimated market value of 2 billion € for landings of European Countries from North East Atlantic, Central East Atlantic, and Mediterranean Sea and Black Sea. This corresponds to approximately 1/3 of the total market value of all landings in EU countries irrespective of their origin.

observations from satellite and large scale plankton samplings have shown declines in phytoplankton([22]) and chlorophyll over the last 20-50 years. For 74% of the worlds permanently stratified oceans the increase in surface warming is accompanied by a reduction in productivity. For northern latitudes an increased production is assumed since large areas will become ice free.

- **Possible impacts on aquaculture**

Climate change can have severe economic implications on marine aquaculture. Bearing in mind that marine aquaculture in the EU is related to a market value around €2 billion there are concerns that climate change will lead to significant economic impacts due to climate change.

Positive and negative effects are expected. Productivity may rise due to increasing growth rates and feed conversion efficiency for some species used in aquaculture. It could also be possible to introduce new species to aquaculture. On the other hand negative effects such as thermal stress for coldwater species and intertidal organisms, diseases and disease susceptibility are expected. Also damages to fish farms due to extreme weather events are possible. It may be necessary to shift production centres to more appropriate locations according to changed environmental conditions. In addition there are concerns that heat waves may cause significant economic impacts in particular to production sites that are situated in shallow water close to the coast. It is unknown as to whether the positive effects will outweigh the negative effects or vice versa.

- **The impacts of industrial fishing on key species**

Many changes in the marine commercial fish stocks have been observed over the last decades in the Atlantic. It is extremely difficult to separate the effects of changes in population density and recruitment and regional climate effects from direct anthropogenic influences like fishing.

Current fishing practice decreases resilience of fish stocks against climate change impacts. Current fishing exerts pressure on older and larger fish and causes evolution of fish populations. This pressure has caused decrease in size and age structure of fish stocks, decrease in resilience against environmental effects and a loss of genetic variability and decreased adaptivity to environmental changes. As a consequence fishing can increase the risks of environmental impacts for fish stocks. ***Environmentally sustainable fishing should aim to protect larger and older fish***.

Sustainably exploited fish stocks can better respond to climate impacts. Uncertainty on future anthropogenic climate change justifies a precautionary approach to fisheries management. Global warming could have significant impacts – positive or negative – on most of the commercial fish stocks. Stocks that are drastically reduced by overfishing are more vulnerable to climatic changes than sustainably exploited stocks. The response of fish stocks to environmental influences depends on population size. Healthy stocks can better adapt to population displacement and changes in ecosystem structure.

A flexible and adjustable fish stock management is needed. A likely scenario for the future of the North Sea is an increase in temperature, high NAO and increased inflow of Atlantic water. This scenario would lead to low recruitment of Atlantic cod, a northward shift of present fish species (cod, herring and sprat) and an invasion of southern species (sardine and anchovy). An important question is how future industrial fishing should be managed in the light of climate

([22]) Planktonic plant.

effects on the marine environment. As several relevant industrial key fish species (such as herring and probably other small pelagic([23]) species) respond highly to varying hydrographic conditions, future fish stock management should be continuous, but flexible and adjustable according to the responses of fish stocks to future environmental conditions. Especially highly migrative species that alter their migration routes due to a changing environment will influence the management needs.

In order to be able to adjust fisheries management in good time, research is needed that improves insight into impacts of climate change on EU fisheries and related prognoses.

- **Policy Options**

Man-made greenhouse gases continue to rise and contribute to a large proportion to climate change. Climate change impacts in many ways directly and indirectly on European industrial fisheries and marine aquaculture. In total a market volume of more than €4 billion is at stake.

There is no doubt that climate change will impact positively and negatively on the marine ecosystem and on the EU fisheries and marine aquaculture. It is uncertain whether the positive or negative impacts of climate change on the EU fisheries will preponderate. In many aspects the knowledge and understanding of relations and interactions between the marine ecosystem, industrial fishing, marine aquaculture and climate change is deficient.

Considering possible policy choices, ***7 general options have been identified*** (they are discussed below):

Option 1. ***No action option***.
Option 2. ***Decrease of greenhouse gases***. Taking legislative and policy measures and supporting existing initiatives to decrease releases of greenhouse gases.
Option 3. ***Strategies to increase resilience of fish populations***. Developing strategies and concepts that enable a sustainable exploitation of fish stocks in a way that fish stocks have a higher resilience to environmental impacts.
Option 4. ***Strategies to improve fish stock management***. Developing flexible fish stock management strategies and concepts that are adjustable to the responses of fish stocks to environmental conditions.
Option 5. ***Strategies to improve aquaculture***. Developing strategies and concepts in order to minimise negative impacts on marine aquaculture.
Option 6. ***Stimulating research***. *S*timulation of relevant research and sharing of knowledge.
Option 7. ***Compensate negative impacts***. Provision of support (financial or other) in order to compensate negative impacts of climate change.

Discussion of the options:

Option 1) As it is not proven that climate change will have an overall negative impact on EU fisheries a possible option could be to take no action at all. The "no action option" has the advantage that it is not related to any initial costs. Positive impacts of climate change on fisheries such as increased production of the marine ecosystem due to increased temperatures will not be foreclosed. On the other hand it appears to be unacceptable not to act at least against

([23]) Fish that spend most of their life swimming in the water column with little contact with or dependency on the bottom. Usually refers to the adult stage of a species.

negative climate change impacts (including cost implications) as these will fully occur without any counteraction. Option 1 is not recommended.

Option 2) This option is related to the support of a European policy to combat climate change (e.g. the EU greenhouse gas monitoring and reporting or the emission trading schemes) and appropriate measures that aim to minimise atmospheric concentrations of greenhouse gases. As greenhouse gas emissions cause climate change, this option will contribute to tackling climate change at its source. Option 2 is recommended.

Option 3) It has been demonstrated that historic and current industrial fishing decreases resilience of fish stocks against environmental changes. Option 3 aims to develop strategies for sustainable fishing in the sense that fish stocks have a higher resilience to environmental changes. This could e.g. be possible by exploring options on how to reduce the catches of older and larger fish or by the establishment of marine protected areas. This option aims to adapt current fish exploitation to respond to impacts of climate change. This is in line with the objectives of the EU Adaptation Programme under the European Climate Change Programme (ECCP) to explore options to improve Europe's resilience to climate change impacts in different sectors. The Common Fisheries Policy (CFP) has a key role in managing fish populations and should take possible climate impacts on fish stocks into account. It could be an appropriate instrument to implement corresponding strategies to increase the resilience of fish stocks against impacts from climate change. Option 3 is recommended.

Option 4) Fish stocks will respond to climate change by specific behaviour e.g. with time or spatial shifts of fish stock abundance or changes in migration routes. Option 4 aims to react in fish stock management to the responses of fish stocks in order to allow an efficient exploitation. This will require a flexible regime of fish stock management in order to avoid negative economic impacts. This option aims to adapt current fish stock management to impacts of climate change and is therefore in line with the objectives of the EU Adaptation Programme under the ECCP. It is vital to take into account the sustainability aspects in the sense of option 2. Otherwise there is a risk, that the improved fish stock management will be used to maximise the exploitation of marine resources without taking account of the need to increase the resilience of fish stocks against environmental impacts. As for option 3, the CFP could be instrumental in implementing corresponding strategies. Option 4 is recommended.

Option 5) Similar to options 3 and 4, this option is an adaptation strategy in line with the EU adaptation programme under the ECCP. It aims to avoid negative impacts on marine aquaculture. Possible elements of the strategy may e.g. be to move production centres northwards, to move production sites to deeper and cooler water or to focus on new species. Similar to options 3 and 4, the CFP could be instrumental in implementing corresponding strategies. Option 5 is recommended.

Option 6) In particular options 3 to 5 are related to significant research needs. It is indispensable to have appropriate knowledge and insight in relations and interactions between the marine ecosystem, industrial fishing, marine aquaculture and climate change. A sound knowledge base is a prerequisite for the development of efficient strategies for sustainable fishing, fish stock management and for marine aquaculture in view of the threats of climate change. Specific research needs are listed in chapter 4. The EU could stimulate and/or support corresponding research in order to improve the factual basis for its policy decisions and the strategies to be developed and could contribute to the dissemination of the created knowledge. Option 6 is recommended.

Option 7) This option concerns the provision of support (financial or other) in order to compensate negative impacts of climate change such as compensation payments for regions where significant economic impacts have occurred as an impact of climate change (e.g. due to outfalls of aquaculture production after heat waves or due to breakdown of fish recruitment in a region if a fish population has regionally disappeared). Such payments could provide short term help to the region concerned. However, compensation measures are reactive and not directed to the future. Proactive and knowledge-based approaches seem to be preferable (e.g. altered aquaculture production strategies or fish exploitation management. Option 7 is not recommended.

Table 1 gives an overview of the identified policy options and their pros and cons.

Table 1: Overview of policy options and their pros and cons

Policy option	Pros	Cons	Recommendation
1. No action	▪ No costs ▪ Positive impacts will contribute to economic profits	▪ Impacts will occur without any counteraction; this is acceptable for possible positive impacts but not for negative ones.	Not recommended
2. Decrease greenhouse gases	▪ In line with international and EU policy objectives ▪ Combats impacts on fisheries at the source of climate change	▪ Possible impact on EU competitiveness if EU policy measures go further than international action	Recommended
3. Strategies to increase resilience of fish	▪ Will contribute to lower potential impacts on fish stocks ▪ knowledge based proactive approach ▪ In line with the EU's adaptation programme ▪ Implementation possible under the Common Fisheries Policy (CFP)	▪ Knowledge gaps and obstacles need to be resolved	Recommended
4. Strategies to improve fish stock management	▪ Will contribute to lower economic impacts on EU fisheries ▪ knowledge based proactive approach ▪ In line with the EU's adaptation programme ▪ Implementation possible under the CFP	▪ Knowledge gaps and obstacles need to be resolved ▪ Risk that the improved possibilities of fish stock management will be used for increasing the exploitation of fish stocks, disregarding the needs for sustainability	Recommended
5. Strategies to improve aquaculture	▪ Will contribute to lower economic impacts on EU marine aquaculture ▪ knowledge based proactive approach ▪ In line with the EU's adaptation programme ▪ Implementation possible under the CFP	▪ Knowledge gaps and obstacles need to be resolved	Recommended
6. Stimulation of research and sharing of knowledge	▪ improvement of the decision basis for policies and strategies ▪ dissemination of knowledge ▪ supports options 3 to 5	▪ Research budgets may not be spent in a well targeted way	Recommended
7. Compensate negative impacts	▪ contributes to lower economic impacts of climate change impacts	▪ Reactive approach; no stimulation of future oriented measures	Not recommended

Source: BIPRO/IFM-GEOMAR, 2007.

Table 2: Climate change driven phenomena related to specific trends, effects, literature references and their confidence

Id	Phenomenon	Trend	Effect	Literature	Confidence
Properties of the seawater					
1	Greenhouse Gas	Increase, contributes to global warming	Contributes to global warming	IPCC 2007, Karl & Trenberth 2003	High
2	North Atlantic Oscillation	unpredictable	Affects environmental conditions at all trophic levels	Hurrell *et al*. 2006	Low
3	Temperature	Global increase	”	IPCC 2007	High
4	– *Baltic Sea*	Increase (2°C-4°C)	”	BACC 2006	High
5	– *North Sea*	Increase (1.6°C – 3.9°C)	”	Sheppard 2004	High
6	– *Mediterranean*	Increase	”	Hoeppfner *et al*. 2006	Medium
	Salinity		”		
7	– *Baltic Sea*	Decrease	”	BACC 2006	High
8	– *North Sea*	Increase/decrease	”	ICES 2006	Low
9	– *Mediterranean*	Increase	”	Eisenreich 2005	Medium
10	Sea water level	Global rise	Coastal erosion	IPCC 2007	Medium
11	Ocean pH	Decrease	Reduced calcification	Caldeira & Wickett 2003	High
12	Thermo haline circulation	Decrease	Weakened boundary currents, temperature decrease in North East Atlantic	Bryden *et al.* 2005, WGBU report 2006	Low
	Stratification				
13	*Baltic Sea*	Increase	Reduced nutrients, effects on primary production	BACC 2006	Medium
14	*North Sea*	Increase	Reduced nutrients, effects on primary production	Beare 2002	Medium
15	*Mediterranean*	Increase	Reduced nutrients, effects on primary production	Bethoux *et al.* 2002	Medium

Id	Phenomenon	Trend	Effect	Literature	Confidence
Biology of key species					
	Fluctuation in species dominance related to NAO				
16	– *North Sea*	Increase	Switch from herring to sardine	Alheit & Hagen 1997, Beare *et al.* 2004	High
17	– *North Sea*	Decrease	Gadoid outburst	Cushing 1984	High
	Distribution of industrial key species				
18	– *North Sea*	Northward shift	Loss of stocks	Perry *et al.* 2006, Southward *et al.* 1996	High
19	– *North Atlantic*	Range extension	Higher productivity	Drinkwater 2006	Medium
20	– *North Atlantic*	Migration change	Gain or loss of stocks	Sissener and Bjorndal 2005	Medium
21	– *Mediterranean*	Migration to colder waters	Loss of “cold biota”	Bombace 2001, Dulcic *et al.* 1999	High
22	Reproductive pattern	Later spawning	Match/mismatch with food	Cushing 1984	Medium
23	Reproductive pattern	Opportunistic homing	Change of spawning location	Ravier & Fromentin 2004	Medium
24	Invasion of southern species	Increase	Change in fisheries target species	Perry *et al.* 2005	High

Id	Phenomenon	Trend	Effect	Literature	Confidence
Biological environment					
25	Invasion of exotic species	Increase	Replacement of native species	Helmuth *et al.* 2006, Nehring 2003	Low
26	Phenology([24])	Shift towards earlier spring bloom	Match/mismatch	Edwards and Richardson 2004	Medium
27	Disturbed trophodynamics	Increase in trophic mismatch	Reduced recruitment success	Beaugrand 2003	Low
	Primary Productivity				
28	– *Global*	Increase/decrease	Increase in secondary and tertiary production	Sarmiento *et al.* 2004, Behrenfeld *et al.* 2006	Low
29	– *Northern Latitude*	Increase	Increase in secondary and tertiary production	ACIA 2005, Hoepffner *et al.* 2006	Medium
Recruitment					
30	Impact of temperature	Increase/decrease (optimum temperature for each species)	Productivity decrease or increase	O'Brien *et al.* 2000, Planque and Fredou 1999	High
	Shifts in zooplankton prey species				
31	– *Baltic Sea*	Ecosystem shifts	increase/decrease in secondary and tertiary production	Möllmann *et al.* 2005	High
32	– *North Sea*	Ecosystem shifts	increase/decrease in secondary and tertiary production	Beaugrand 2004	High
33	– *Mediterranean*	Ecosystem shifts	increase/decrease in secondary and tertiary production	Molinero *et al.* 2007	Medium

([24]) The science that treats the periodic biological phenomena with relation to climate, especially seasonal changes.

Id	Phenomenon	Trend	Effect	Literature	Confidence
Productivity					
	Impact on aquaculture				
34	– *Productivity*	Increase	Economic benefit	Lehtonen 1996	medium
35	– *production facilities*	Northward displacement	Economic loss	Stenevik and Sundby 2006	medium
	Collapse of fisheries				
36	– *North Sea*	YES, if species near limits of range extension	Loss of stocks at regional level	Drinkwater 2005	Low
	Recovery of stocks				
37	– *North Atlantic (cod)*	Failure due to species shift	Loss of stocks	Drinkwater 2006	Low
Fisheries					
38	Impact of fisheries	Decrease in size and age structure	Reduced recruitment	Berkeley *et al.* 2004, Birkeland & Dayton 2005	High
39	Impact of fisheries	Decrease in resilience	Reduced recruitment	Hsieh *et al.* 2006	Medium
40	Impact of fisheries	Loss of genetic variability	Reduced plasticity to environmental changes	Hauser *et al.* 2002	Low

Source: BIPRO/IFM-GEOMAR, 2007.

List of acronyms

NAO	North Atlantic Oscillation
ICES	International Council for the Exploration of the Sea
psu	practical salinity units with no dimension attached
SST	Sea Surface Temperature
CFP	Common Fisheries Policy
ECCP	European Climate Change Programme
CPR	Continuous Plankton Recorder

Glossary

Abiotic environment	The non-living environment, comprised by all abiotic factors, e.g. temperature, salinity
Acidification	Decrease of the pH; the pH is a measure of the acidity or alkalinity of a solution
Advection	Transport by the mean current, as opposed to eddy diffusion or spreading by dispersion
Benthic	Refers to animals and fish that live on or in the water bottom
Benthos	Organisms attached to or resting on the bottom or living on the bottom sediments
Bioclimatic envelope approach	Determined through techniques that correlate current species distribution with climate variables or through an understanding of the individual's physiological response to climate change
Biogeography	Describes the distribution of organisms on earth and analyzes the causes of the geographical distribution of living and extinct taxa;
Biogeographical barrier	Change in the environment, that hinders an organisms to spread further
Biotic	Live and living organisms
Biotic environment	The living environment, comprised by all biotic factors, e.g. food, predators
Bloom	When related to phytoplankton, a sudden and rapid increase in biomass of the plankton population. Seasonal blooms are essential for the aquatic system productivity. Sporadic plankton blooms can be toxic
Cephalopods	Animals (molluscs) with tentacles converging at the head, around the mouth (squids, cuttlefish, octopus)
Cladocerans	Group of small planktonic crustaceans found mainly in freshwater, e.g. daphnia. Marine species do occur, e.g. podon, living as zooplankton
Convection	Vertical circulation in a gas or liquid under influence of instability
Copepods	The largest class of crustaceans. Either free living or parasitic. Dominate the zooplankton but also occur with benthic species
Cyanobacteria	Synergistic blue-green algae. Group of bacteria
Demersal	Living in close relation with the bottom and depending on it
Diatoms	Microscopic single-celled algae which have two ornate interfitting outer 'shells' containing silica
Dinoflagellates	Group of planktonic algae
Euphotic zone	The superficial layer of the ocean within the range of effective light penetration (for photosynthesis)
Euryhaline	Organism that lives in a wide range of salinities

Eurytherm	Organism that lives in a wide range of temperatures
Eutrophication	Generally, the natural or man-induced process by which a body of water becomes enriched in dissolved mineral nutrients (particularly phosphorus and nitrogen) that stimulate the growth of aquatic plants and enhances organic production of the water body. Excessive enrichment may result in the depletion of dissolved oxygen and eventually to species mortality and replacements
Flagellates	Group to which dinoflagellates belong; also euglenida, raphidophyta
Gadoid (species)	Group of fish species belonging to the family gadidae, e.g cod, haddock
Gregarious	Relating to a social group
Halocline	Region below the surface layer of the sea or lake, where the salinity gradient increases abruptly (i.e. where salinity decreases rapidly with increasing depth).
Holoplankton	plankton with a completely pelagic life cycle
Interspecific	Between different species, e.g. competition
Intraspecific	Within one species, e.g. competition
Meroplankton	temporary plankton consisting of pelagic stages of organisms which also have benthic stages. Mainly larvae of sedentary organisms
Nao	The North Atlantic Oscillation is a dominant atmospheric behaviour in the North Atlantic; for explanation see footnote 9
Neritic	Relates to the ocean domain above the continental shelf and top edge of the continental slope. Corresponds to nearshore waters.
Neritic species	Species with a life cycle and distribution largely confined to the continental shelf and upper slope
Pelagic	Fish that spend most of their life swimming in the water column with little contact with or dependency on the bottom. Usually refers to the adult stage of a species
Phenology	The science that treats the periodic biological phenomena with relation to climate, especially seasonal changes
Phytoplankton	Planktonic plant
Plankton	Floating organisms whose movements are more or less dependent on currents. While some zoo-plankton exhibit active swimming movements that aid in maintaining vertical position, plankton as a whole is unable to move against appreciable currents
Precipitation	Meteorology: the falling products of condensation in the atmosphere, such as rain, hail or snow

Primary production	Assimilation (gross) or accumulation (net) of energy and nutrients by green plants and by organisms that use inorganic compounds as food
Radiative forcing	see footnote 31; is defined as the difference between the incoming radiation energy and the outgoing radiation energy in a given climate system. A positive forcing (more incoming energy) tends to warm the system, while a negative forcing (more outgoing energy) tends to cool it
Recruitment	The number of fish added to the exploitable stock, in the fishing area, each year, through a process of growth (i.e. the fish grows to a size where it becomes catchable) or migration (i.e. the fish moves into the fishing area)
Salinity	The relative concentration of salts, usually sodium chloride, in a given soil or water. Freshening in this context refers to a decrease of salts in the water. Unitless; sometimes the old unit psu (practical salinity unit) is still used
Secondary production	The rate of production of herbivorous animals by conversion of their vegetable food into animal tissue
Skipped spawning	A fish that already participated in reproduction, but skips one or more seasons
SRES marker scenarios	Specific climate scenarios as described in the special report on emissions scenarios
Stratification (of the water column)	The occurrence of more or less horizontal water layers in the sea as a consequence of differences in density, i.e. salinity (halocline) or temperature (thermocline)
Taxon	a taxon is a group of organisms in biological systematic
Tertiary production	The rate of production of carnivorous animals by conversion of their animal food into their own tissue
Thermal equator	The line that circumscribes the earth and connects all points of highest mean annual temperature to their longitudes
Thermocline	Region below the surface layer of the sea or a lake, where the temperature gradient increases abruptly (i.e. where temperature decreases rapidly with increasing depth). A thermocline may reach the surface and become a front. It is usually an ecological barrier and its oscillations have significant consequences on stocks distribution and ocean productivity.
Thermohaline circulation	Circulation in the ocean that is driven by the density differences caused by temperature and salinity differences
Transition zone	Refers to biogeography; a zone between two distinctly different habitats. Often a barrier for distribution
Trophic level	Classification of natural communities or organisms according to their place in the food chain. Green plants (producers) can be roughly distinguished form herbivores (consumers) and carnivores

Tropical precipitation belt	The tropical precipitation belt is situated at the equator from 30° South to 30° North. Following the sun's zenith point the rainy season is oscillating to the northern boundary in northern summer and respectively to the southern boundary in southern summer (northern winter), leading to wet seasons close to the sun's zenith and to dry seasons far away from that point.
Zooplankton	Planktonic animal

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1. Project background

Climate change is expected to result in several processes that in turn can have an impact on the biological productivity of the marine ecosystems, and can also result in modifications of the area of distribution of marine resources.

Consequences of climate change for the fishing industry could be significant. The impact on fisheries of changes in the biological productivity of marine ecosystems will vary between fisheries. They will depend of the specific environmental changes that occur and the particular biological characteristics of each species. Changes in a particular marine environment may become conducive to a rapid growth of high value species found in that environment, while the reverse may be true in other instances.

The effects of climate change on fisheries will affect a sector that is already characterised by full utilisation of resources, large over-capacity of many fleet segments and conflicts amongst fishers, and between fisheries and others uses of marine ecosystems. Changes in the productivity of the ecosystem will have a profound effect on the sustainability of the fisheries and climatic factors may have amplified declines through negative productivity change. They may now be influencing fish stock recovery.

Climate changes are the target of very extensive research being carried out by various groups, including government agencies, universities, and focus groups. This knowledge is important for estimating how fish stocks will develop in the future and in order to quantify the relationships involved.

Against this background the purpose of the present study is to provide the Committee on Fisheries with a clear and detailed analysis of the probable impacts and consequences of climate change on European Union fisheries.

The study reviews the existing literature on the effects of climate change on fisheries, with particular reference to the fisheries resources that are relevant for the European Union fisheries both in the Atlantic and in the adjacent seas (Mediterranean, North Sea and Baltic).

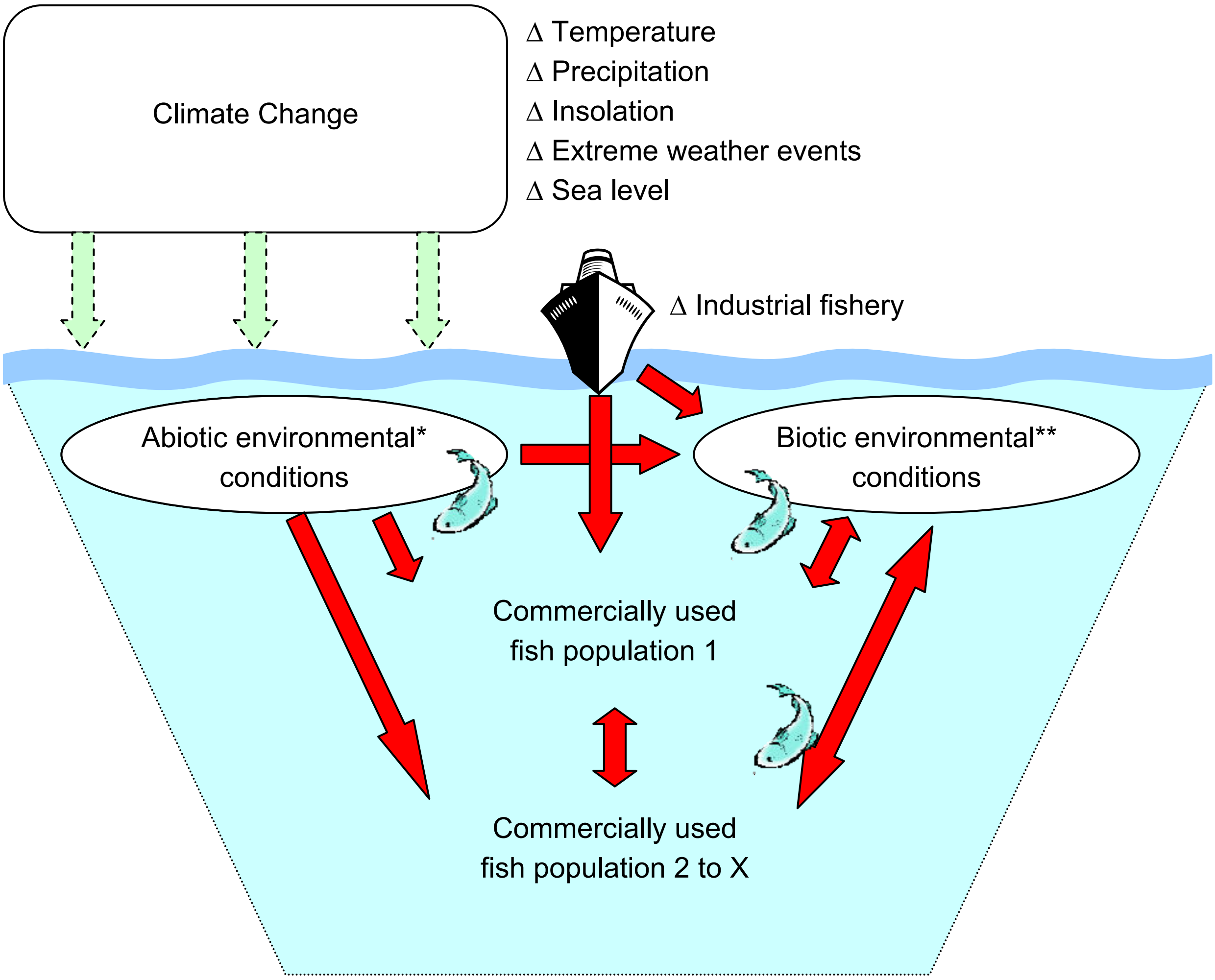
The study includes a conceptual framework describing the key processes driving the dynamics of the ecosystems and the fisheries resources which has been used to systematically review the literature of the effects of climate change on the key species relevant for the European Union fisheries. The analysis includes a revision of the existing literature on elements like habitat, food supply, predators, pathogens, and competitors that could constrain the distributions of species. Furthermore it contains a description of properties of the water such as temperature, salinity, hydrographical structure, currents, alkalinity (ocean acidification) or oxygen availability. Specific effects on semi-enclosed seas – such as the Baltic, Mediterranean, Aegean, and northern Adriatic are taken into consideration.

2. Conceptual framework

The conceptual framework is used as a basis to determine the focal points of an objective-driven literature review, the documentation and evaluation of the results and the drawing of conclusions.

The framework is based on the relevant key processes and causal chains driving the dynamics of marine ecosystems and fisheries resources. Figure 1 illustrates these key processes and causal chains.

Figure 1: Relevant Key Processes and Causal Chains Driving the Dynamics of Marine Ecosystems and Fisheries Resources



Source: FAO Statistics 2005 and ICCAT 2005.

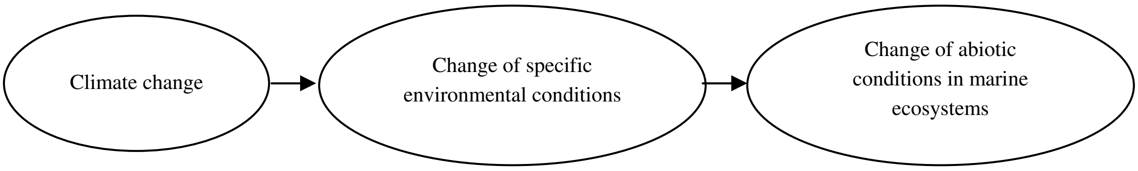
* *The non-living environment, comprised by all abiotic factors, e.g. temperature, salinity.*

** *The living environment, comprised by all biotic factors, e.g. food, predators.*

Principal driving forces that influence the development of the fisheries resources are in the context of the study specific environmental conditions that are due to climate change. One should keep in mind that the effects of environmental changes on fish populations are substantially depending on the size and the structure of the stocks considered. They are thus heavily influenced by the fishery. The driving forces impact directly or indirectly on commercially used fish populations. As a consequence, the future development of fisheries resources has to be considered against probable developments of the climate and industrial fishery activities.

Climate change causes changes of specific environmental conditions, in particular of temperature, precipitation, insolation, extreme weather events and the sea level:

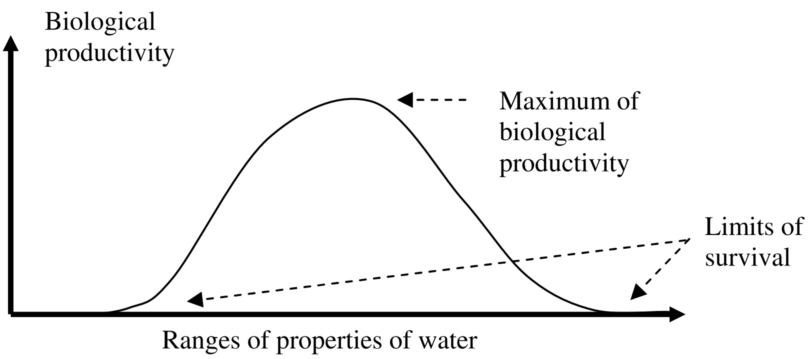
These specific environmental conditions influence directly the abiotic conditions in marine ecosystems. In the project context and with respect to marine ecosystems particularly the properties of water, i.e. temperature, salinity, alkalinity, availability of oxygen, hydrographical structure and currents are crucial. This can be considered as the principal causal chain to relate climate change to the marine ecosystem:



Changes of specific environmental conditions can be identified and can be related to changes of the abiotic conditions in marine ecosystems, i.e. to the properties of water. According to climate change scenarios, the future development of properties of water can be estimated.

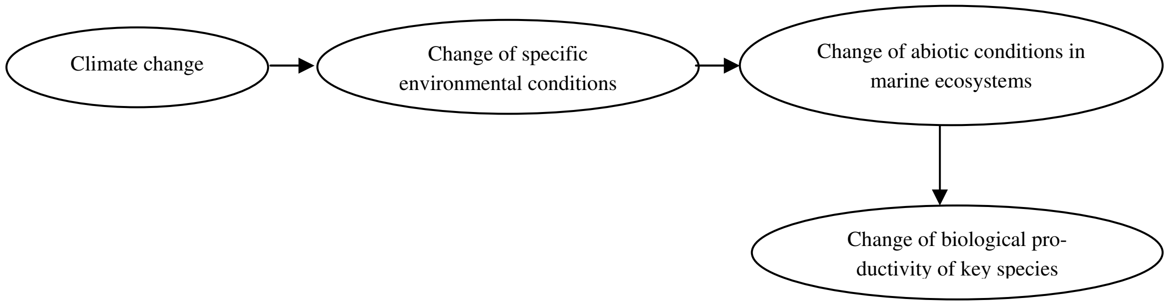
Each species has biological characteristics with respect to its habitat ([25]) which may vary during a species' life cycle. In the marine environment the most relevant biological characteristics are the properties of water as each fish species has a specific range of temperature, salinity, structure, currents and availability of oxygen. The biological characteristics describe ranges under which conditions a species can survive at minimum up to optimum conditions. According to the biological characteristics of the species there is an optimum combination concerning the properties of water that determines the maximum of biological productivity. According to the physiological requirements of the key species it is possible to assess environmental impacts on the physiological performance, the migration behaviour and the reproduction success.

Figure 2: Biological Productivity in Dependence of the Properties of Water



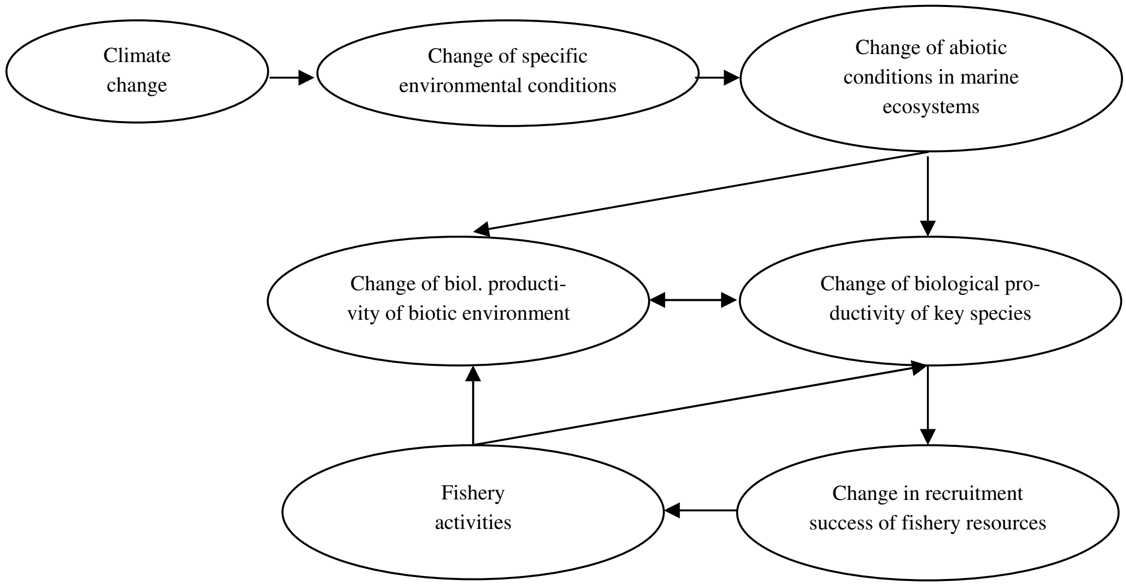
[25] Understood as the physical environment that surrounds a population.

These considerations allow supplementing of the principal causal chain:



The properties of water are also directly linked to the biological productivity of the biotic environment([26]), i.e. of all marine organisms, including exploited fish populations and of any other organism that interacts with these fish populations such as food organisms, competitors, predators or pathogens. These interactions and the effects of fisheries on these interactions have to be taken into account against the final objective to assess the effects of climate change on industrial fisheries.

The principal causal chain relating climate change with industrial fishery can be completed:



The geographical scope of the study concerns the fisheries resources that are relevant for the European Union fisheries in the Atlantic and in the adjacent seas (Mediterranean, North Sea and Baltic). It shall comprise specific effects on semi-enclosed seas i.e. the Baltic, Mediterranean, Aegean, and northern Adriatic.

The properties of water vary significantly within this research area and also probable changes of the properties of water will differ within the area. The variations influence the geographical distribution of fisheries resources. In this context also aspects such as the following have to be taken into consideration within the literature research:

- processes in the boundary areas between the warm and cold water masses;
- changes in the position of the ocean fronts, where water masses with different characteristics meet one another, their role as barriers to the spread both of the water masses themselves and of plankton and fish, and the effects of these changes;

([26]) The living environment, comprised by all biotic factors, e.g. food, predators.

- displacements of transition zones([27]) and simultaneous discontinuities in the local occurrence of some species;
- changes in abundance and distribution of existing and new populations;
- changes in geographical range extensions or in the geographical distribution of fish populations linked to hydro-climatic variation and regional climate warming;
- effects such as longer growing seasons, lower natural winter mortality and faster growth rates;
- evidences and predictions of possible local shifts in production centres and mixes of species as well as geographical displacements and internal changes in ecosystems;
- modification in established reproductive patterns, migration routes, and ecosystem relationships;
- exotic fish entering the ecosystem and probable changes in species composition and competition;
- changes in distribution and migration patterns, and their influence on mixture of species, the competition for food and the whole food web, as well as the consequences of area overlaps in closely related species;
- effects of regional climate warming on recruitment via changes at the base of the food web, identifying the more sensitive species on the availability and the assemblage of planktonic food during the pelagic larval stages of main species;
- effects of climate change on aquaculture.

The results of the literature review are documented under three sub-headings of chapter 3:
- 3.1 Expected changes of properties of water;
- 3.2 Expected effects of climate change on key species;
- 3.3 Other related issues.

The future development of the properties of water within the research area is crucial for the future availability and distribution of fisheries resources. Thus the literature review has a focal point related to the properties of water (see chapter 3.1). Specific aspects in this review are in particular:
- Prognoses/models for climate change and establishing relations to specific environmental conditions in aquatic ecosystems, in particular to properties of water;
- Analysis of information provided by models about changes in current patterns in particular the probable processes in the boundary areas between the warm and cold water masses;
- Description of the probable changes in the position of the ocean fronts, where water masses with different characteristics meet one another, their role as barriers to the spread both of the water masses themselves and of plankton and fish, and the effects of these changes;
- Analysis of the impacts of warming based on the evidences of displacements of transition zones and simultaneous discontinuities in the local occurrence of some species;
- Specific effects in semi-enclosed seas.

As mentioned above the biological productivity of exploited fish is connected to climate change via changes in the properties of water and the biological characteristic of the fish species. Having in mind the complexity of the subject it is useful to focus the literature review on several key species with relevant importance to the fisheries industry in the European Union. The key

([27]) Refers to biogeography; a zone between two distinctly different habitats. Often a barrier for distribution.

species should adequately represent the research area in order to assess the probable impacts on the fisheries industry.
Against this background Table 3 shows a selection of relevant industrial key fish species based on the relevance with respect to catches and geographical distribution and some relevant economic information on the individual species. The economic information shows that the selected species caught in the study area are related to a market value amounting to approximately €2.3 billion. Prices are guide prices of the European Commission from 2005 and do not necessarily reflect the real price achieved at the market for the species in this year.

Table 3: Selection of key species, their area of relevance and economic information

Key species	Area of relevance in the study scope	Landings 2005([28]) (tonnes)	Guide price 2007 (€/tonne)	Value (€m)	Share (%)
Atlantic herring	North East Atlantic, North Sea, Baltic Sea	829,764	260	215,7	9,6
Sprat	North East Atlantic, North Sea, Baltic Sea, Mediterranean	703,119	160	112,5	5,0
European pilchard	North East Atlantic, Central East Atlantic, Mediterranean	245,168	587	143,9	6,4
European anchovy	North East Atlantic, Central East Atlantic, Mediterranean	111,403	1270	141,5	6,3
Atlantic mackerel	North East Atlantic, Mediterranean	289,994	314	91,1	4,1
Northern bluefin tuna	Atlantic, Mediterranean	20,727	1500([29])	31,1	1,4
Blue whiting	North Sea, Mediterranean	462,258	946	437,3	19,5
Atlantic cod	North East Atlantic, North Sea, Baltic Sea	125,245	1615	202,3	9,0
European hake	North East Atlantic, North Sea, Central East Atlantic, Mediterranean	76,252	3731	284,5	12,7
Sandeel	North Sea	166,755	1000([30])	166,8	7,4
Haddock	North East Atlantic	44,533	983	43,8	1,9
Saithe	North East Atlantic	59,377	751	44,6	2,0
European plaice	North East Atlantic, North Sea	66,566	1499	99,8	4,4
Round sardinella	Central East Atlantic, Mediterranean	90,282	1000([30])	90,3	4,0
Atlantic horse mackerel	North East Atlantic, Mediterranean	177,345	400([30])	70,9	3,2
Skipjack tuna	Atlantic, Mediterranean	46,453	630([29])	29,3	1,3
Yellowfin tuna	Atlantic, Mediterranean	35,214	1207([29])	42,5	1,9
Totals		**3,552,821**		**2,248**	**100**

Source: FAO Statistics 2005 and ICCAT 2005.

([28]) Landings of European Countries from North East Atlantic, Central East Atlantic, and Mediterranean Sea and Black Sea; Landings from 2005 were taken from FAO Fisheries Department, Fishery Information, Data and Statistics Unit, extracted with FISHSTAT Plus (Universal software for fishery statistical time series Version 2.3 2000).
([29]) Price from ICCAT (International Commission for the Conservation of Atlantic Tunas), 2005.
([30]) Estimated price.

Landings of industrial fisheries in EU-15 amounted in 2004 to approximately 4.5 billion tons and the related market value was approximately €6 billion (Facts and figures on the CFP, European Commission 2006). These figures are related to all landings in European ports, irrespective of their origin. Within the present study the economic impacts will be discussed for the study area (i.e. a related market value of approximately €2 billion). However it is noteworthy that climate change does not stop at catching areas and related impacts are also to be expected beyond the study area.

The future development of the key fish species can be assessed on the basis of the biological characteristics of each species. Depending on their physiological plasticity, species will tolerate changes or enhance or decrease their productivity. Organisms may migrate to areas which are more suitable for their demands. This can lead to local shifts in production centres and geographical displacement affecting the distribution of common fishing grounds. Lower winter temperatures as predicted by the climate change scenarios could prolong the growing season leading to an increase in growth rate and productivity. Higher winter temperatures could decrease the winter mortality and lead to an increase in productivity. To evaluate these relationships, information on the biological characteristics of the key species have to be collected and synthesized. This enables to define whether the species in question has already reached its limit of survival and will change in abundance and distribution. The ecological niche with respect to temperature, salinity, alkalinity or oxygen availability of a fish species can be defined by lethal, controlling (physiology), and directive (behaviour) criteria. The lethal criteria usually have wider ranges whereas controlling and in particular directive criteria may have very narrow ranges. If fish encounter habitats with unsuitable abiotic conditions, they respond behaviourally and attempt to move into areas closer to their preferred biological characteristics.
As a consequence it is expected, that changes in abiotic conditions as an effect of climate change will lead to change in abundance and distribution of industrial fish species. Shifts in the species composition in a given environment can lead to changes in the interaction within the ecosystem. They will lead to changes in the predator/prey relationships and competition e.g. for food or favourable habitats. Among others, such interactions are taken into consideration in the literature review in chapter 3.3.

Chapter 3.2 concerns the literature review related to expected effects of climate change on key species relevant for EU fisheries in the research area. According to the conceptual framework, the review will cover the following aspects:

- Biological characteristics of industrial key fish species;
- Estimation of probable changes in abundance and distribution of existing and new populations;
- Analysis of the evidences and probable changes in geographical range extensions or in the geographical distribution of fish populations linked to hydro-climatic variation and regional climate warming;
- Estimation and localisation of probable effects such as longer growing seasons, lower natural winter mortality and faster growth rates;
- Description of localisation of modification in established reproductive patterns, migration routes, and ecosystem relationships;
- Description of the evidences and predictions of possible local shifts in production centres and mixes of species as well as geographical displacements and internal changes in ecosystems.

For the assessment of the future evolution of the biological productivity for each species the most relevant elements of the biotic environment such as food supply, competitors, predators or pathogens have to be taken into consideration. The future development of the key fish species and the elements of the biotic environment can be assessed on the basis of the biological characteristics of each species (fish and species of the biotic environment).

The literature review also takes further relevant issues into account. Industrial fishing directly impacts on the biological productivity and the adaptivity to environmental changes of the key fish species. Thus the availability of fisheries resources depend on future fishing activity. Climate change may cause changes in migration routes and changes and extensions in the geographical ranges of species that may lead to exotic species entering into the ecosystem. The invasion of exotic species can result in competition for living space and food and might cause the displacement of other species originally using the habitat. Changes in the food web structure have to be expected. Climate change will also influence the distribution and occurrence of pathogens and parasites.

Furthermore, the changes in the environment may also affect species exploited in aquaculture and related industry.

Table 4 shows a selection of the most relevant species in aquaculture based on the relevance with respect to production and area of relevance and some relevant economic information on the individual species. The economic information shows that the selected species are related to a market value amounting to approximately €2 billion.

Table 4: Selection of most relevant aquaculture species, their area of relevance and economic information

Key species	Area of relevance in the study scope	Production 2005	Price	Value	Share (value)
		(tonnes)	(€/tonne)	(€m)	(%)
Atlantic salmon	North East Atlantic	144.778,00	324,37	446,33	22,47
Gilthead seabream	North East Atlantic, Mediterranean	70.010,00	251,71	278,14	14,00
Pacific cupped oyster	North East Atlantic, Mediterranean, Black Sea	127.150,00	471,17	269,86	13,59
Blue mussel	North East Atlantic	361.399,00	1.372,42	263,33	13,26
European seabass	North East Atlantic, Mediterranean and Black Sea	47.982,00	205,31	233,70	11,77
Japanese carpet shell	North East Atlantic, Mediterranean and Black Sea	68.006,00	332,29	204,66	10,31
Mediterranean mussel	Mediterranean and Black Sea	108.522,00	1.083,49	100,16	5,04
Rainbow trout	North East Atlantic	23.664,00	418,83	56,50	2,84
Atlantic bluefin tuna	North East Atlantic, Mediterranean and Black Sea	3.665,00	89,50	40,95	2,06
Turbot	North East Atlantic	6.792,00	171,95	39,50	1,99
Grooved carpet shell	North East Atlantic, Mediterranean and Black Sea	6.282,00	206,44	30,43	1,53
European flat oyster	North East Atlantic	4.647,00	357,19	13,01	0,66
European eel	North East Atlantic, Mediterranean and Black Sea	1.122,00	118,86	9,44	0,48
Totals		974.019,00		1.986,01	100,00

Source: FAO Statistics 2005.

In 2003 the production of aquaculture in EU-25 amounted to approximately 1.4 billion tons and the related market value was approximately €2.8 billion (Facts and figures on the CFP, European Commission 2006). These figures cover the overall aquaculture production including freshwater. Within the present study the economic impacts will be discussed for marine aquaculture (i.e. for an estimated market value of approximately €2 billion).

Chapter 3.3 concerns the literature review related to other relevant issues in the research area. The review will cover the following aspects:

- Biological characteristics of relevant species of the biotic environment of industrial key fish species (i.e. food organisms, competitors, predators, etc.), of exotic fish possibly entering the research area and of key species used in aquaculture.
- Estimation of possible exotic fish entering the ecosystem and probable changes in species composition and competition.
- Expected effects of climate change on the biological productivity and its seasonality.
- Influence of environmental conditions and fisheries on recruitment success of key species.
- Impact of future fishing activities.
- Study of the probable changes in distribution and migration patterns, and their influence on mixture of species, the competition for food and the whole food web, as well as the consequences of area overlaps in closely related species.
- Analysis of the effects of regional climate warming on recruitment via changes at the base of the food web, identifying the more sensitive species on the availability and the assemblage of planktonic food during the pelagic larval stages of main species.
- The evidences and probable effects of climate change on aquaculture.

Based on the literature research, the results will be synthesized and critically assessed with respect to impacts of climate change on European fisheries and on marine ecosystems. Possible impact of climate change on EU fisheries will be assessed.

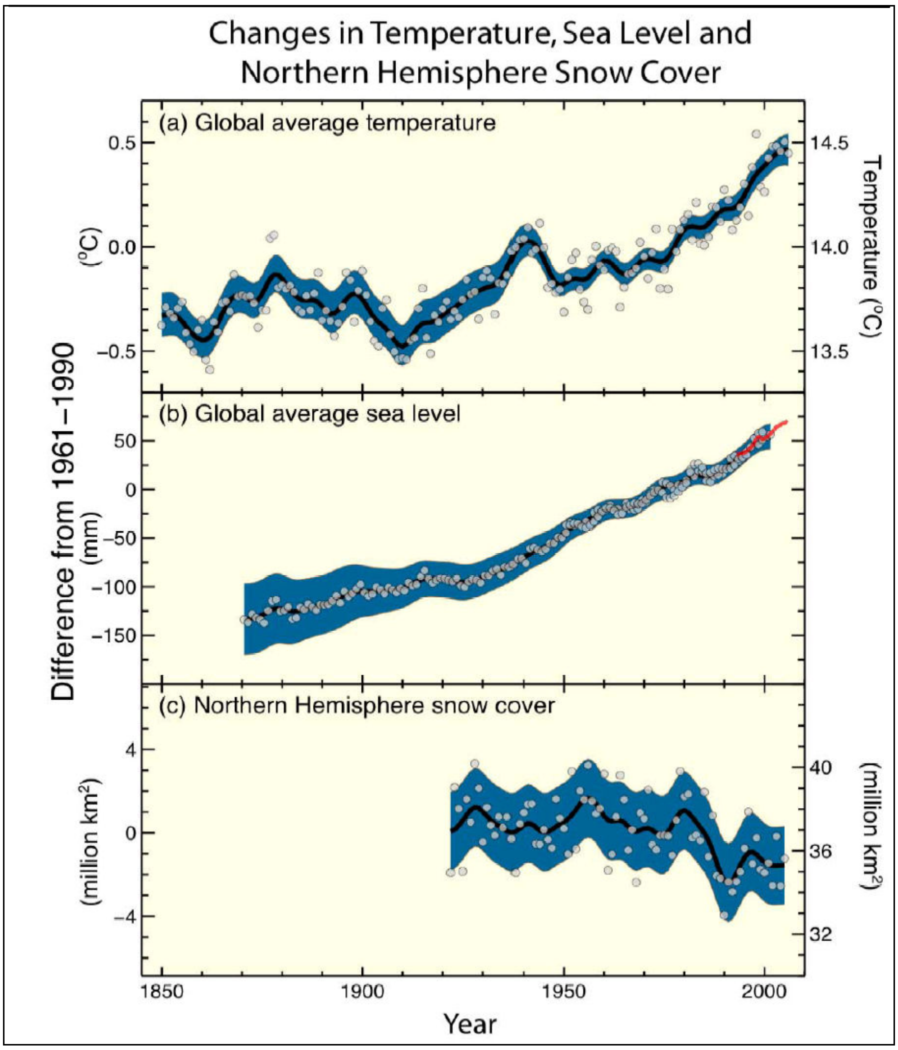
3. Literature review

3.1 Expected changes of properties of water

Prognoses for climate change

Climate change is considered to be one of the threats to biodiversity and to the structure and functioning of ecosystems (McCarthy *et al.*, 2001; Vitousek, 1994). Although the causes and likely impacts are subject to debate (Sharp, 2003; Veizer, 2005), the scientific consensus is that climate change is real (Houghton *et al.* 2001; Karl & Trenberth 2003; King 2004; Walther *et al.* 2005, IPCC report 2007). Warming of the climate system has been detected in changes of surface and atmospheric temperatures, reduction of the snow cover in the northern hemisphere, temperatures in the upper several hundred metres of the ocean and in contributions to sea level rise (IPCC report 2007, Figure 3), ocean acidification (Caldeira and Wicket 2003, 2005) and changes in salinity (MCCIP 2006).

Figure 3: Changes in Temperature, Sea Level and Snow Cover.



Source: IPCC 2007.
Notes: Observed changes in (a) global average surface temperature; (b) global average sea level rise from tide gauge (blue) and satellite (red) data and (c) Northern Hemisphere snow cover for March-April. All changes are relative to corresponding averages for the period 1961-1990. Smoothed curves represent decadal averaged values while circles show yearly values. The shaded areas are the uncertainty intervals estimated from a comprehensive analysis of known uncertainties (a and b) and from the time series (c).

The role of greenhouse gases

A large proportion of the recent increase in global temperature has been associated with increased inputs of several atmospheric gases. The global atmospheric concentrations of carbon dioxide, methane and nitrous oxide have increased markedly as a result of human activities since 1750 and now far exceed pre-industrial values determined from ice cores spanning many thousands of years (Houghton et al. 2001; Hulme et al. 2002; IPCC report 2007, Raper et al. 1997, Siegenthaler et al. 2005; Spahni et al. 2005).

These so-called greenhouse gases are naturally present in the atmosphere, and are important for life on earth. Carbon dioxide (CO_2) is the most important anthropogenic greenhouse gas, its global atmospheric concentration has increased from a pre-industrial value of about 280 ppm to 379 ppm in 2005 (IPCC 2007). The atmospheric concentration of carbon dioxide in 2005 exceeds by far the natural range over the last 650,000 years (180 to 300 ppm) as determined from ice cores (Siegenthaler et al. 2005). The annual carbon dioxide concentration growth-rate was larger during the last 10 years (1995–2005 average: 1.9 ppm per year), than it has been since the beginning of continuous direct atmospheric measurements (1960–2005 average: 1.4 ppm per year, IPCC 2007).

Greenhouse gases allow short-wave radiation from the sun to pass through the atmosphere and heat the earth, and also to retain some of the radiation that is subsequently emitted from the warmed surface of the earth (Kiehl & Trenberth 1997). Anthropogenic greenhouse gas emissions have contributed to an increased retention of energy (an enhanced greenhouse effect), warming of the planet, and an increase in global temperature (Karl & Trenberth 2003; Raper et al. 1997; Ruddiman & Thomson 2001). The globally averaged net effect of human activities since 1750 has been one of warming, with a radiative forcing([31]) of 1.6 Wm^{-2}. The combined radiative forcing due to increases in carbon dioxide, methane, and nitrous oxide is 2.30 Wm^{-2}, and its rate of increase during the industrial era is very likely to have been unprecedented in more than 10,000 years. The carbon dioxide radiative forcing increased by 20% from 1995 to 2005, the largest change for any decade in at least the last 200 years (IPCC report 2007).

Emissions of greenhouse gases continue to rise, and although it is unclear exactly how global climate will change in the future, considerable international effort is being directed into predicting future climatic conditions (Houghton et al. 2001, Hulme et al. 2002, IPCC 2007).

Temperature

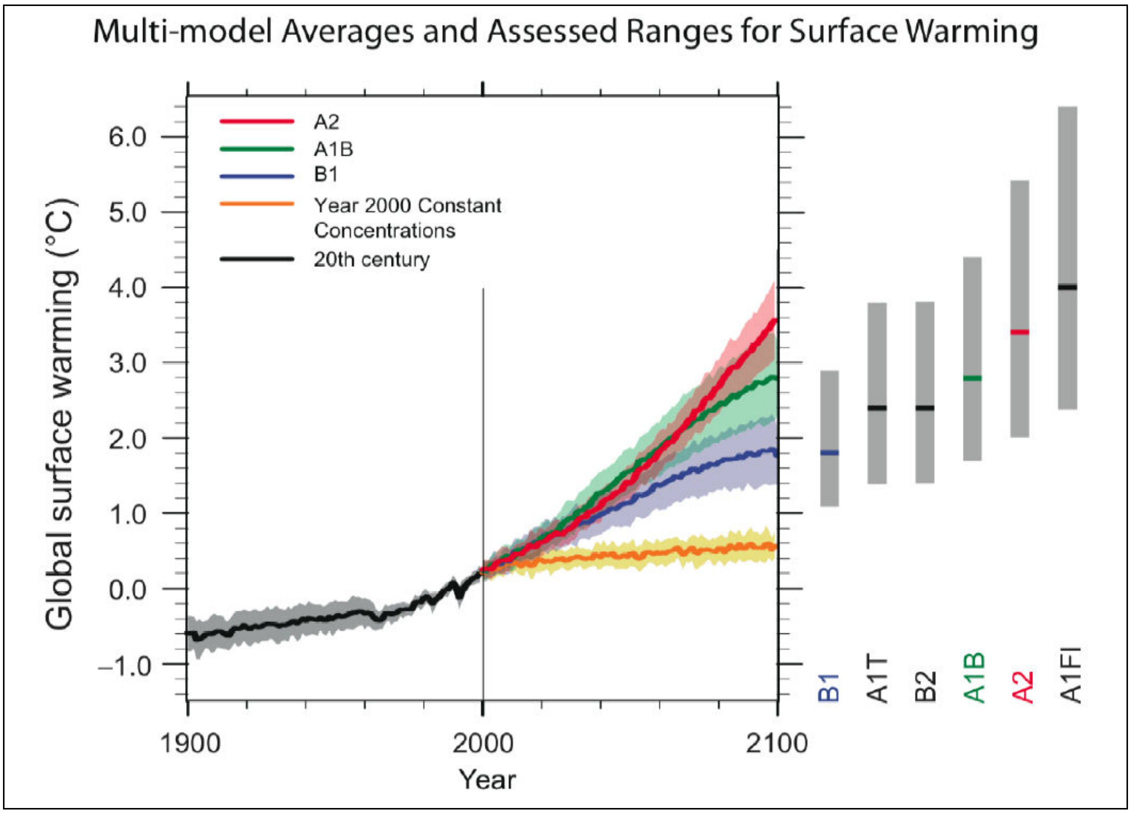
Average global temperatures have increased by ~0.6°C over the past century (Houghton et al. 2001; Hulme et al. 2002). During this period, both marine (Levitus et al. 2000) and freshwater systems (Winder & Schindler, 2004) have warmed.

The coastal marine climate of Europe is predicted to continue to warm throughout the 21st century, with the forecast for the sea surface temperature to increase by 0.2°C per decade (IPCC 2007, Figure 4). Oceanographic studies from the Baltic Sea show that the mean annual sea surface temperatures could increase by 2° to 4°C by the end of the 21st century (BACC 2006). A significant increase in average temperatures of the waters of the western Mediterranean basin over the last 20-30 years has been found (Francour et al. 1994). The IPCC report also stresses that the warming trends are occurring faster on continental shelves, the areas where the

([31]) "radiative forcing" is defined as the difference between the incoming radiation energy and the outgoing radiation energy in a given climate system. A positive forcing (more incoming energy) tends to warm the system, while a negative forcing (more outgoing energy) tends to cool it.

commercially important fish stocks live, than in open ocean areas. Climate change is already causing detectable changes in ocean pH, temperature, circulation patterns and nutrient loading from storm events (IPCC 2007). The summer of 2003 was probably Europe's hottest summer in over 500 years with temperatures up to 3°C-6°C above long-term means and an annual precipitation of 50% below average leading to a 30% reduction in gross primary productivity over Europe (Ciais et al. 2005, Schär et al. 2004). Approximately 22,000 to 45,000 heat related deaths in humans occurred across Europe over two weeks in August 2003 (Patz et al. 2005). This heat wave was well outside the range of expected climate variability and could not be explained by natural drivers alone. (Stott et al. 2004) have concluded that summer warmings are caused by anthropogenic effects and summers like 2003 are likely to be experienced more frequently in the future. By the end of the century they predict that the situation in the year 2003 would be classed as an anomalously cold summer relative to the new climate.

Figure 4: Prognoses for Surface Warming.



Source: IPCC 2007.

Notes: Solid lines are multi-model global averages of surface warming (relative to 1980-99) for the scenarios A2, A1B and B1, shown as continuations of the 20th century simulations. Shading denotes the plus/minus one standard deviation range of individual model annual averages. The orange line is for the experiment where concentrations were held constant at year 2000 values. The grey bars at right indicate the best estimate (solid line within each bar) and the likely range assessed for the six SRES marker scenarios([32]). The assessment of the best estimate and likely ranges in the grey bars includes the AOGCMs in the left part of the figure, as well as results from a hierarchy of independent models and observational constraints.

Sea level rise

There is high confidence that the rate of observed sea level rise increased from the 19th to the 20th century. The total 20th century rise is estimated to be 0.17 m. Global average sea level rose at an average rate of 1.8 mm per year from 1961 to 2003. The rate was even faster from 1993 to

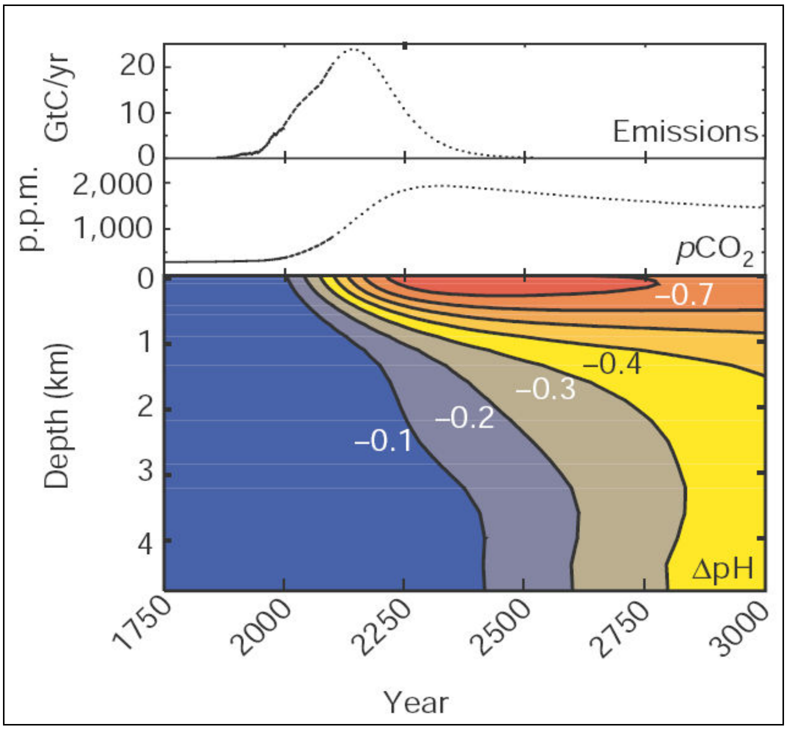
([32]) Specific climate scenarios as described in the special report on emissions scenarios

2003 with about 3.1 mm per year. Whether this faster rate reflects decadal variability or an increase in the longer-term trend is unclear.

Acidification

In the past 200 years the oceans have absorbed half of the anthropogenic CO_2 which caused a reduction of surface water pH of 0.1 units, equivalent to a 30% increase in hydrogen ions (The Royal Society 2005). Continuous uptake of atmospheric CO_2 is expected to substantially decrease oceanic pH over the next few centuries. This will lead to changes in the saturation horizons of aragonite, calcite and other minerals essential to calcifying organisms (Feely *et al.* 2004). Experimental evidence is indicating that if these trends continue, key marine organisms such as corals and some plankton organisms will have difficulties maintaining their external calcium carbonate skeletons which could lead to a change in structure and biodiversity of the different ecosystems (Orr *et al.* 2005, Riebesell *et al.* 2000). We know very little about the direct effects of acidification on fish. The response is likely to be on acidosis of the body tissue and impaired metabolic function. Eggs and larval stages are likely to be more susceptible than adults. Therefore it is suggested that reduced reproductive success will be among the first symptoms to appear. Model estimates of pH reduction in the ocean surface, depending on the CO_2 emission scenarios being used, range from 0.3 to 0.5 units over the next 100 years and from 0.3 to 1.4 units over the next 300 years (Caldeira & Wickett 2003, 2005, Figure 5)

Figure 5: Prognosis for Ocean Acidification.



Source: Caldeira & Wickett 2005.
Notes: Atmospheric CO_2 emissions and historical atmospheric CO2 levels with predicted CO2 concentrations (IPCC 2001) and change in pH in the ocean in different water depth derived from model runs.

Although many marine organisms have managed to adapt to thermal fluctuations in the last few million years, the expected changes in pH are higher than any pH changes inferred from fossil records over the past 300 million years (Caldeira & Wickett 2003, Feely *et al.* 2004). Marine acidification is of particular concern for the European seas, since 23% of the global marine anthropogenic CO_2 is expected to be absorbed in the North Atlantic near surface waters (Sabine *et al.* 2004). Additionally, the problem of acidification in semi-enclosed European Seas and in coastal waters will be intensified due to release of more acidic compounds introduced by river systems and the atmosphere (Hoepffner *et al.* 2006).

Climate change effects on bivalves are expected to occur due to increase in ocean acidification, which will affect the calcification process in the shells and could have an effect on growth and reproduction.

Salinity

In general, increase in ocean salinity is difficult to predict, but changes in precipitation, evaporation, ocean circulation and ice melt have the potential to have an impact on salinity (MCCIP 2006). In the nordic seas a decrease in salinity has already been observed in recent years (Curry & Mauritzen 2005, Peterson *et al*. 2006), but according to modelling, this trend is still too weak to have an impact on Atlantic current patterns. For the future, increased winter precipitation is expected, leading to a tendency of decreases in salinity for the water bodies of the Baltic Sea.

In the last century the Mediterranean has seen a 20% reduction in precipitation (Eisenreich 2005). Since evaporation losses are higher than the input via precipitation and river discharges, an increase in salinity in the Mediterranean is expected. Salinity data were collected in the northernmost part of the Mediterranean Sea, in the Gulf of Triest (northern Adriatic Sea) over a time period of 1991- 2003 by Malacic *et al.* (2006) and showed an increase of 0.28-0.34 per year. When excluding the 2003 data, which was a very dry and hot year (see chapter 3.1 – *Prognoses for climate change*), the salinity values showed an increase of 0.22-0.28 per year.

In combination with over-fishing the ongoing increase in temperature and the increase in man-made emission of CO_2, leading to acidification of the oceans, are a threat for the already weakened fish stocks (WBGU Report 2006).

Key message 1

It is scientific consensus that climate change is reality. **Temperatures will increase and sea level will rise.** Warming of the climate system has been detected in changes of surface and atmospheric temperatures, temperatures in the upper several hundred metres of the ocean and in contributions to sea level rise. Average global temperatures have increased by ~0.6°C and sea level has risen 0.17m over the past century. During this period, both marine and freshwater systems have warmed. The coastal marine climate of Europe is predicted to continue to warm throughout the 21st century, with the forecast for the sea surface temperature to increase by 0.2°C per decade. **Model estimates predict ocean acidification**. The pH reduction in the ocean surface range from 0.3 to 0.5 units over the next 100 years and from 0.3 to 1.4 units over the next 300 years. **Salinity will change.** In the nordic seas and the Baltic decreases in salinity are expected whereas in the Mediterranean salinity is expected to increase.

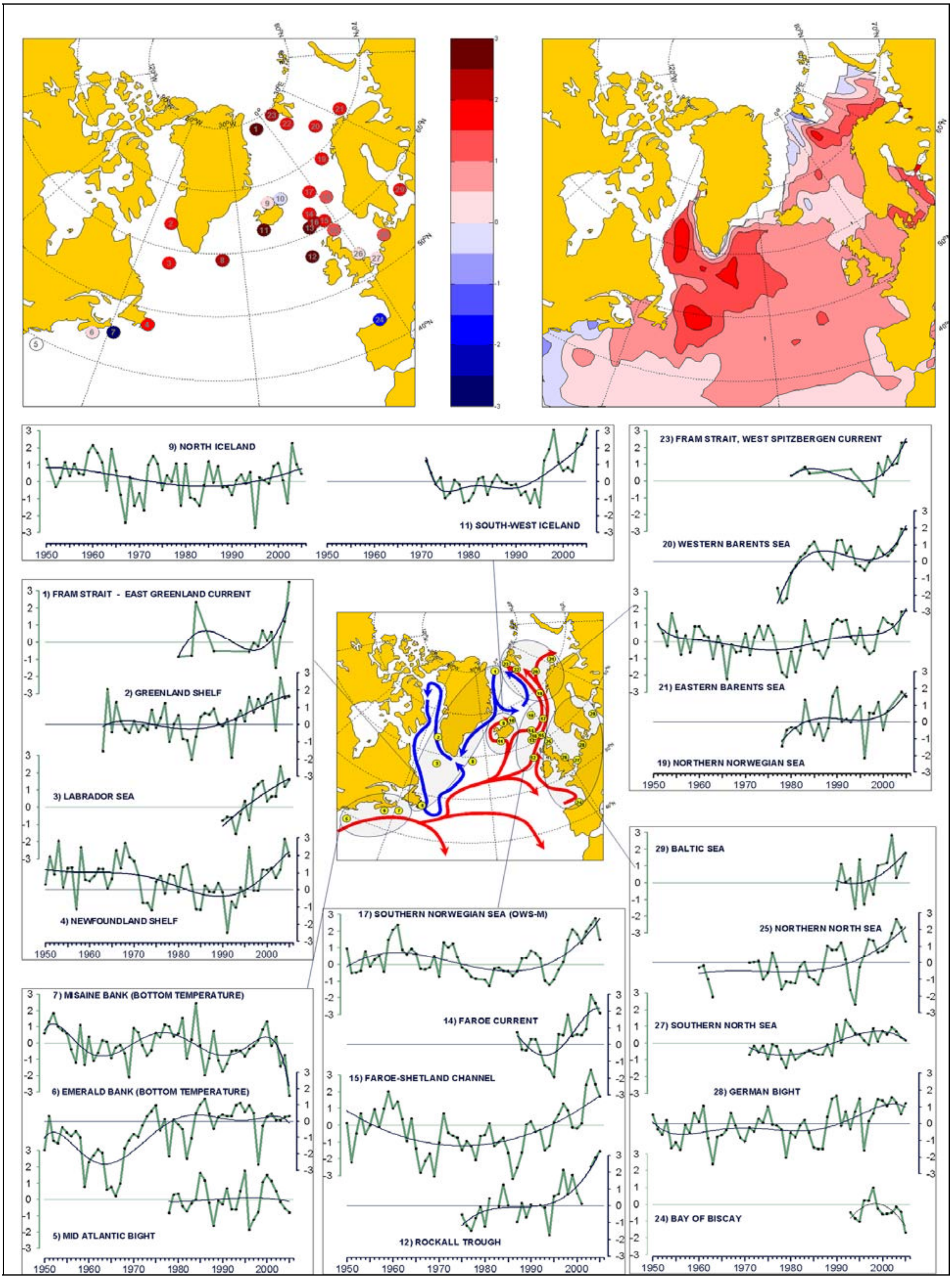
Man-made greenhouse gases continue to rise and contribute a large proportion to climate change. They are a threat for the already weakened fish stocks and releases should be minimised.

Changes in current patterns

Ocean currents, fronts, up-welling areas and down-welling zones play a significant role in the distribution and production in marine ecosystems and these features are likely to change in response to alterations in temperature, precipitation, runoff, salinity and wind (Scavia *et al.* 2002).

There are marked regional differences in the predicted levels of warming, but northern latitudes are predicted to be the most affected (Houghton *et al*. 2001).

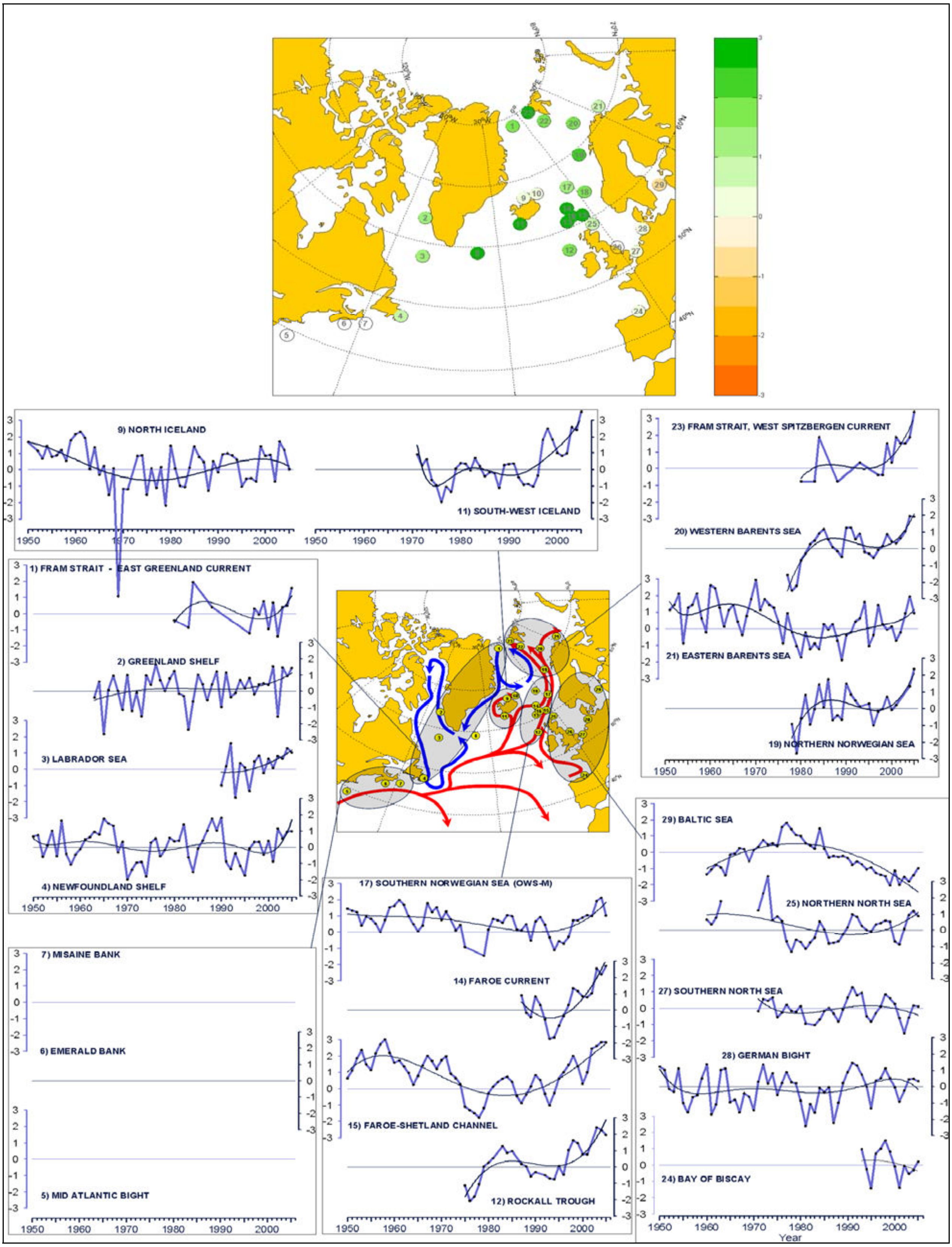
Figure 6: Temperature Anomalies.



Source: ICES 2006.

Notes: Upper ocean temperature anomalies across the North Atlantic. Temperature data are presented as anomalies from the long-term mean; section and station anomalies are normalised with respect to the standard deviation, e.g. a value of +2 indicates 2 standard deviations above normal (top-left map (see Figure #3 for a legible version) and curves); sea surface temperature data are anomalies in °C (top-right map). The maps show conditions in 2005 (colour intervals 0.5, reds are positive/warm and blues are negative/cool).

Figure 7: Salinity Anomalies.



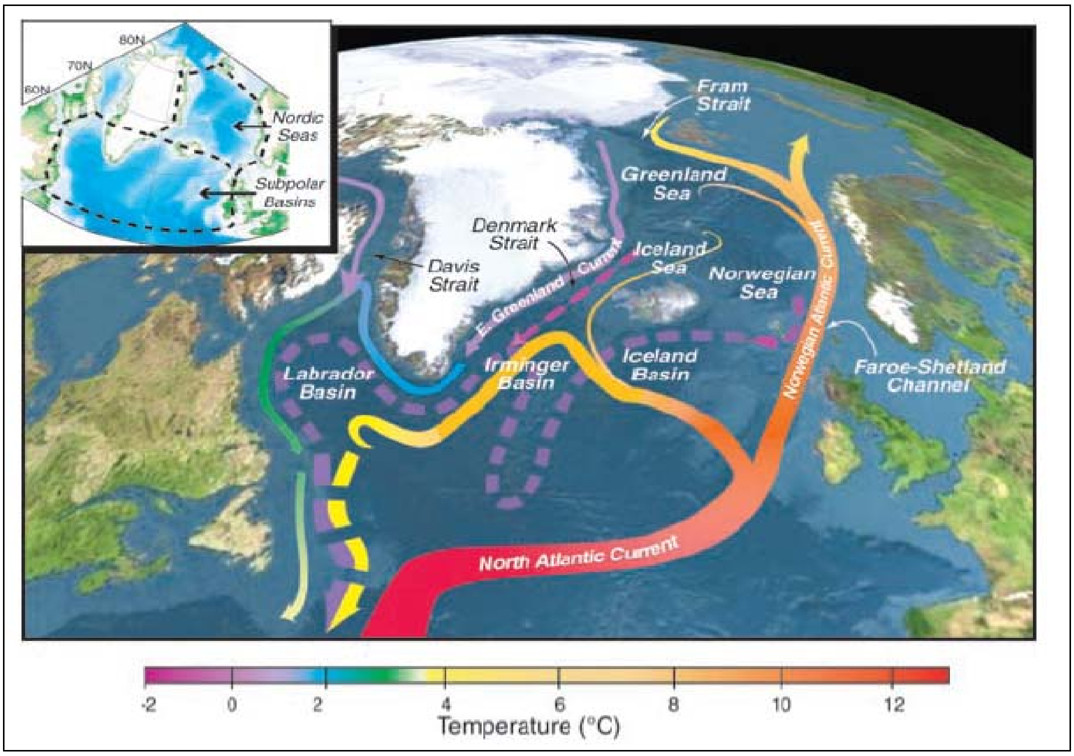
Source: ICES 2006.

Notes: Upper ocean salinity anomalies across the North Atlantic. Salinity data are presented as anomalies from the long-term mean; for consistency, anomalies are normalized with respect to the standard deviation, e.g. a value of +2 indicates 2 standard deviations above normal. The maps show conditions in 2005 (colour intervals of 0.5, greens are positive/saline, orange are negative/fresh); the curves show selected time-series. See Figure #3 for a legible version of the top map.

At continental, regional, and ocean basin scales, numerous long-term changes in climate have been observed (Harrods *et al.* 2007). These include changes in Arctic temperatures and ice, widespread changes in precipitation amounts, ocean salinity, wind patterns and aspects of extreme weather including droughts, heavy precipitation, heat waves such as in summer 2003 and the intensity of tropical cyclones. Scientific evidence collected over the last two decades is indicating that environmental changes are occurring at all scales with profound impacts on European seas and coast (IPCC report 2007). The water bodies that border Europe, the North Atlantic, the Arctic and the Mediterranean, are under the influence of both subtropical and arctic regions and regional adjustments of the current patterns of the water bodies to the physical parameters due to climate change are expected. Warming conditions in the boundary areas have been observed over the last decade and analysed by the ICES Working group on Oceanic Hydrography over the last years and are updated on a yearly basis. Results from the latest report are shown in this study (ICES Cooperative Research Report, 2006, Figure 6 and Figure 7).

The water bodies of the North Atlantic and Arctic regions are the home of various fish species of great commercial importance. The North Atlantic current, which the Gulf Stream is part of, carries warm and saline waters northwards from the mid-latitude North Atlantic towards and into the Arctic region (Figure 8) and helps maintain large areas ice free. This water returns back to the North Atlantic partly as a surface outflow and mainly as a deep overflow which is directed southward through several depressions and channels as a cold and bottom-near current. It becomes the main contributor to the North Atlantic Deep water, which is an essential component controlling the global thermohaline circulation of the oceans. Huge water masses currently sink from the surface to the great depths in the nordic seas and the Labrador seas. From there the water flows southwards at a depth of 2-3 km to the Southern Ocean (Rahmstorf 2002). To balance this loss of water, warm surface water flows from the South into the northern latitude regions. (Figure 9).

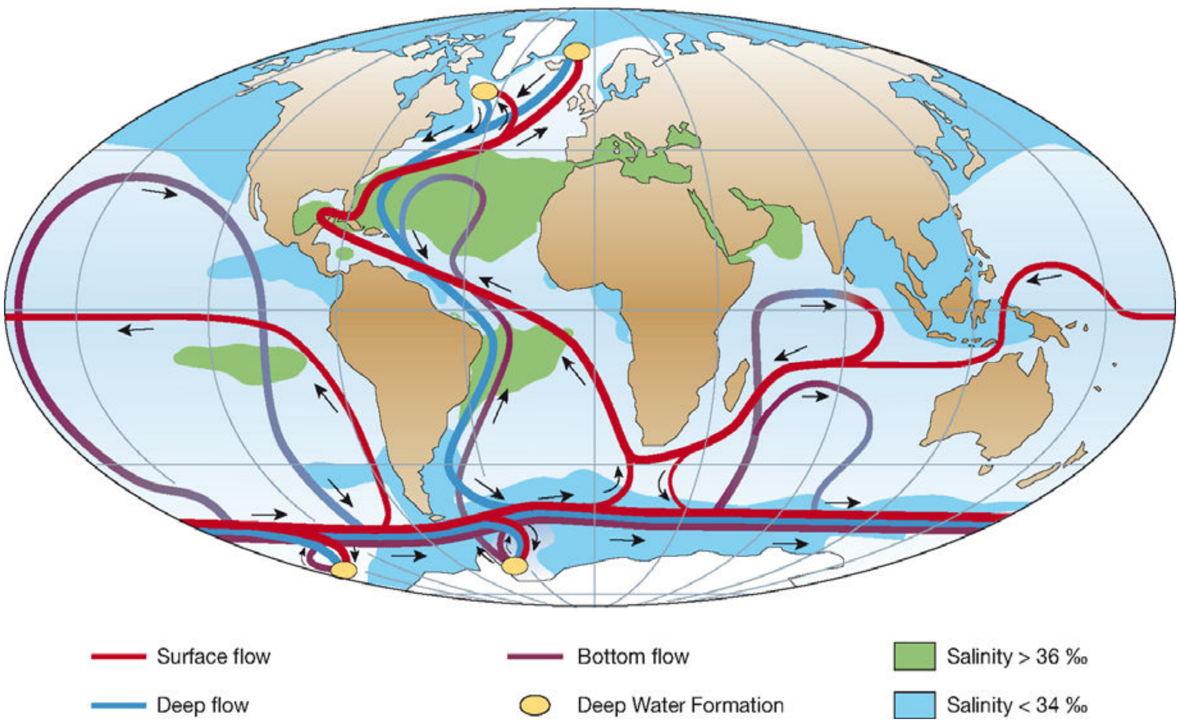
Figure 8: Ocean Currents of Nordic and Sub-polar Basins.



Source: Curry and Mauritzen 2005.
Notes: Topographic map of Nordic seas and sub-polar basins with schematic circulation of surface currents (solid curves) and deep currents (dashed curves) that form a portion of the Atlantic MOC. Colours of curves indicate approximate temperatures. Map inset delineates the boundaries of the Nordic seas and sub-polar basins used in the volumetric analysis (dashed black lines).

Global climate change affects this water flow by decreasing the density of seawater in two ways: firstly, the temperature increase causes a thermal expansion of the water and secondly, increased precipitation and melt water input dilute the seawater with freshwater. This decrease in salinity and thus in density can retard the sinking of water in the North Atlantic, the so-called deep water formation.

Figure 9: Global Ocean Currents.



Source: WBGU 2006.
Notes: The thermohaline circulation driven by temperature and salinity differences.

In the nordic seas a decrease in salinity has already been observed in recent years (Curry & Mauritzen, 2005), but according to modelling, this trend is still too weak to have an impact on Atlantic current patterns. Debate exists as to whether the results by Bryden et al. (2005) suggesting that the circulation in the Atlantic may already have weakened by 30% are correct, since the results don't agree with modelling calculations or with the changes in sea-surface temperatures. But if trends in warming and salinity-decrease should continue to strengthen in the coming decades, this may actually lead to a noticeable weakening of the Atlantic current over the course of this century and in an extreme case to a total cessation in deep water formation (WGBU report 2006). If this occurs, the North Atlantic current and the greater part of the Atlantic heat transport would shut down and would significantly change the temperature distribution throughout the whole Atlantic.

As a result of dynamic adaptation of the sea surface to altered currents, the sea level in the North Atlantic would rise up to 1m and slightly fall in the Southern hemisphere, This redistribution of water would not have an immediate effect on the global sea level average (Levermann et al. 2005), but over the long term the global average would rise by an additional 0.5m due to the gradual warming of the deep ocean after the loss of input of cold water.

Additionally the tropical precipitation belt ([33]) would very likely shift because the thermal equator ([34]) would drift southwards (Claussen et al. 2003). The breakdown in the North Atlantic currents is a risk that is difficult to calculate. One critical factor in the model simulation is the amount of fresh water that will enter the North Atlantic in the future which will depend on the speed of the Greenland ice sheets melting (WGBU 2006).

Key message 2

The water bodies that border Europe, the North Atlantic, the Arctic, and the Mediterranean, are under the influence of both subtropical and arctic regions. Regional adjustments of the current patterns of the water bodies to the physical parameters due to climate change are expected.

The Atlantic thermohaline circulation will be weakened. The water bodies of the North Sea and Arctic regions interact by exchange of cold and warm water flows are driven by the Atlantic thermohaline circulation. The flow intensity is influenced by climate change. Currently the flow intensity may already be reduced by 30%. It is unlikely that the circulation will shut down completely which would have strong impacts on current patterns (e.g. a short term sea level rise in the North Sea of 1m, a long term global sea level rise of 0.5m, a southward shift of the tropical precipitation belt and a reduction of biomass in the Atlantic by 50%). The assessment and prognoses of the impacts is related to significant uncertainties. Scenarios on how possible changes of the thermohaline circulation may impact on the marine ecosystems have not been developed so far.

Changes in the position of the ocean fronts and their role as barriers

Stratification of the water column leads to natural barriers where organisms can concentrate or where organisms have to pass through. Stratification intensity is positively correlated with salinity and temperature and enhanced stratification suppresses nutrient exchange through vertical mixing (Behrenfeld *et al*. 2006). The North Sea is most vertically stratified around its eastern fringes, along the Belgian, Dutch, Danish, German and Norwegian coasts because of freshwater input from the Baltic Sea and continental rivers. Increased freshwater flux will increase stratification. This will increase the energy needed to mix the water vertically resulting in a shallower mixed layer and less mixing with deeper water causing reduced replenishment of nutrients (Scavia *et al.* 2002).

Stratification peaks each year during late summer due to solar warming of the sea surface. Increase in temperature could lead to changes in timing and strength of stratification (MCCIP 2006). In the south western North Sea near the entrance to the English Channel the water column is permanently mixed because of its shallowness and the influence of tidal flow. Over the last 5 decades (1951–1998), the North Sea has become steadily more stratified west of ca 5° while to the east it has become steadily less stratified, mirroring the long-term change in salinity (Beare *et al.* 2002).

Trawl data from Scottish research vessels dating from January 1925 show that catches of the warm water pelagic species, anchovy (*Engraulis encrasicolus*), sardine (*Sardina pilchardus*) and red mullet, species normally only rare in Northern Europe, increased suddenly after 1995 (Beare *et al*. 2004). Falling wind speed and rising temperatures leading to increased

([33]) The tropical precipitation belt is situated at the equator from 30° South to 30° North. Following the sun's zenith point the rainy season is oscillating to the northern boundary in northern summer and respectively to the southern boundary in southern summer (northern winter), leading to wet seasons close to the sun's zenith and to dry seasons far away from that point.

([34]) The line that circumscribes the earth and connects all points of highest mean annual temperature to their longitudes.

stratification intensity could have led to increased anchovy and sardine larval survival (Beare *et al*. 2002). The increase in *Calanus helgolandicus* over *Calanus finmarchicus* could also be the cause, since *C. helgolandicus* is a more favourable food for larval anchovy and sardine (Beare *et al.* 2004).

Molinero *et al*. (2005b) noticed an enhancement of the stratification of the water column in the Mediterranean related to the decrease in wind stress and high water temperature during the middle-to-late 1980s. Marty and Chiaverini (2002) also observed an increase of the stratification of the water column linked to high water temperatures in the period 1991 to 1999. The increased temperatures and decreased wind stress reduced nutrients supplied to the upper layers, leading to changes in phytoplankton communities. By compiling data on phytoplankton blooms, Bethoux *et al*. (2002) documented that during low NAO cold years, diatoms([35]) dominate the spring phytoplankton bloom whereas during high NAO warm years diatoms appear to be scarce and the blooms seem to be dominated by flagellates([36]).

Many organisms are more stressed near their species range boundaries and the distribution of these species is expected to change as environmental conditions change (Harley *et al*. 2006). Current mediated dispersal can define many biogeographical boundaries in coastal oceans, despite potentially suitable habitats beyond the dispersal barriers. Marine species range limit may remain stationary even if conditions in habitats beyond the barriers become suitable. Harley *et al.* (2006) suggest that warming associated weakening of alongshore advection([37]) could actually break down certain marine biogeographical barriers that currently prevent range extension (Gaylord & Gaines 2000).

It has to be mentioned that Global Circulation Models driven by climate scenarios have been treating the marine environment and changes in ocean climate in a simplified way. Models are significantly improving, but the resolution for determining the changes in the position of the ocean fronts is not sufficient yet (Brander 2006).

Key message 3

Stratification will increase. It has been demonstrated, that climate change causes increased stratification of the Baltic Sea, the North Sea and the Mediterranean Sea. Stratification of the water column leads to natural barriers where organisms can concentrate or where organisms have to pass through. Stratification increases with increasing salinity and temperature. Increased stratification hinders mixing with deep water and causes reduced replenishment of nutrients.

Changed circulation and stratification will change the geographical distribution of organisms. Currents play an important role in transporting organisms like plankton and fish over large distances and can thus increase their distribution range. On the other hand, currents also act as a biogeographical barrier between the water masses on both sides of a current. They reduce the exchange of organisms across the current. Warming may lead to weakening of alongshore currents, thus decreasing the distribution with the alongshore current, but breaking down the barrier between coastal and offshore water. This may lead to range extension of organisms previously trapped near the coast. All these effects impact (positively or negatively) on primary production.

Available global circulation models driven by climate scenarios have been treating the marine environment and changes in ocean climate in a simplified way. Models are significantly improving, but the resolution for determining the changes in the position of the ocean fronts is not sufficient yet.

([35]) Microscopic single-celled algae which have two ornate interfitting outer 'shells' containing silica.
([36]) Group to which dinoflagellates belong; also euglenida, raphidophyta.
([37]) Transport by the mean current, as opposed to eddy diffusion or spreading by dispersion.

Displacements of transition zones

The planktonic copepod *Calanus finmarchicus* population of the North Sea has collapsed since the late 1950s, while the abundance of temperate Atlantic and neritic species([38]) groups has risen. The fall in the population of *C. finmarchicus* has coincided with a long-term freshening (i.e. decrease in the salinity) and warming of the eastern North Sea and a long-term increase in the salinity of the western North Sea. The changes may be explained by differing origins of Atlantic water entering the North Sea since the late 1950s due to climate change (Beare *at al.* 2002).

One of the main processes to track climate driven changes in the ecology of a species is phenology which involves the timing and pattern of biological cycles. Molinero et al (2007) analysed a 27 year time series of two copepods, *Centropages typicus* and *Temora stylifera,* two dominant pelagic species in the western Mediterranean. These two species show different seasonal patterns driven by temperature. *C. typicus* peaks in spring whereas *T.stylifera* peaks in late summer-autumn. During years of positive NAO the mean annual cycle of *C. typicus* showed a higher abundance with a maximum peak in April indicating that in addition to an increase in abundance the timing had also moved forward to earlier dates. During negative NAO years the abundance of *C. typicus* decreased nearly threefold. The opposite pattern was observed in the case of *T. stylifera*, which showed low abundance during positive NAO years whereas in years characterized by negative NAO the abundance of this species increased twofold and showed an earlier abundance peak.

The probable effects of increased salinity in the Northern Adriatic cannot be predicted. The effect will depend on the tolerance to increased salinity of the different organisms studied and could have an influence on individual species as well as communities or ecosystems. Mobile organism can avoid a potential salinity stress by leaving the area. If the organisms are at their salinity tolerance level already and can't leave the area, reduction in growth and fecundity and problems with osmoregulation might occur (see general ecosystem relationships presented in Chapter 3.2 – *Reproductive patterns, migration routes and ecosystem rrelationships*).

Key message 4

Examples show that the displacement of transition zones due to climate change cause changes in the abundance of species and can even cause the collapse of whole populations.

Specific effects in semi-enclosed seas

Baltic Sea

In the past century there has been a marked increase of air temperature of more than 0.7°C in the Baltic Sea region which is larger than the global mean air temperature increase of 0.5°C. Oceanographic studies show that the mean annual sea surface temperatures could increase by 2° to 4°C by the end of the 21st century (BACC 2006). This temperature increase is coupled with an increase in winter runoff, shorter ice seasons and reduced thickness of ice in rivers and lakes in the Baltic area. For the future, increased winter precipitation is expected, leading to a tendency of decreased salinity for the water bodies of the Baltic Sea.

([38]) Species with a life cycle and distribution largely confined to the continental shelf and upper slope.

The observed temperature changes in the past have been associated with consistent changes in the terrestrial ecosystems, such as earlier spring phenological phases([39]) or northwards species shifts. In the marine ecosystem of the Baltic Sea, this kind of assessment is difficult because of the presence of strong non climatic stressors like eutrophication([40]), fishing and pollutants. But the expected lowering of the salinity (projected to be between 8% and 50%) will have a major influence on distribution, growth and reproduction. Freshwater species are expected to spread into the Baltic Sea area and invaders from warmer seas (like the zebra mussel (*Dreissena polymorpha*) and the North American jelly comb (*Mnemiopsisi leidyi*, Javidpour *et al.* 2006) are expected to enlarge their distribution (BACC 2006).

For the Baltic Sea, projected increase in temperature will lead to changes in growth and reproduction parameters: It is considered possible that increased temperature will stimulate pelagic bacteria growth more than primary production, leading to an increase in the ratio of bacterial biomass to phytoplankton. Diatom blooms will change in species composition in milder winters and diatoms might be replaced by dinoflagellates([41]). Increasing summer temperatures will enhance cyanobacteria([42]) blooms. Elevated winter temperatures may prevent convection([43]) in late winter and early spring with the results that the nutrients are not mixed into the upper euphotic zone([44]). In the Baltic proper with a salinity of 7psu, the maximum density of water occurs at approx. 2.5°C. If the temperature is higher than 2.5°C this will result in the development of a thermocline([45]) and no redistribution of nutrients due to convection will occur. This might result in a shift in species composition in spring (BACC 2006, Pawlak *et al*. 2007).

North Sea

For the North Sea temperatures in the coastal waters are affected by interactions between the atmosphere and the ocean and by freshwater runoffs. Long-term late winter (January, February) sea temperatures have risen markedly in all North Sea areas between the early 1950s and late 1990s. An increase of 0.6°C in annual averaged temperature (land and sea surface) over the last 70-100 years with a substantial increase over the last 20 years has been observed (Hulme *et al.* 2002). Water temperature in the German Bight at Helgoland Roads has increased by 1.3°C during the past 40 years. Cold winters with sea surface temperatures around - 1°C had occurred about once every 10 years up to 1944, but have been observed only once since 1960 (Wiltshire and Manly 2004). Model runs for changes in sea surface for the next 90 to 100 years by Sheppard (2004) predict about 1.6°C to 3.0°C in the Northern North Sea and 3.0°C to 3.9°C in the shallower southern North Sea. Salinity in the North Sea is lowest in the Norwegian Coastal Current and south-eastern North Sea due to freshwater input from the Baltic, Elbe, and Rhine. Seasonally, salinity is variable, but tends to be highest in late winter (Turrell *et al.* 1992). A general trend remains unclear (ICES 2006).

([39]) "Phenological phases" describe the timing and pattern of biological cycles.
([40]) Generally, the natural or man-induced process by which a body of water becomes enriched in dissolved mineral nutrients (particularly phosphorus and nitrogen) that stimulate the growth of aquatic plants and enhances organic production of the water body. Excessive enrichment may result in the depletion of dissolved oxygen and eventually to species mortality and replacements.
([41]) Group of planktonic algae.
([42]) Syn. blue-green algae. Group of bacteria.
([43]) Vertical circulation in a gas or liquid under influence of instability.
([44]) The superficial layer of the ocean within the range of effective light penetration (for photosynthesis).
([45]) Region below the surface layer of the sea or a lake, where the temperature gradient increases abruptly (i.e. where temperature decreases rapidly with increasing depth). A thermocline may reach the surface and become a front. It is usually an ecological barrier and its oscillations have significant consequences on stocks distribution and ocean productivity.

Mediterranean Sea, Aegean, and northern Adriatic

The Mediterranean Sea is a mid latitude semi enclosed deep basin with two major interacting sub basins, the western and the eastern which are connected by the Strait of Sicily. It has been characterized as a "Miniature Ocean" and has been considered as an ideal test basin due to its rapid response to external forcing (Bethoux *et al*. 1999).

The circulation of the Mediterranean is determined by the exchange of water and heat with the atmosphere through the sea surface and exchange with the adjacent seas through the straits. The thermohaline circulation in the Mediterranean is driven by buoyancy exchanges and the negative heat and freshwater budget. Evaporation exceeds precipitation and river runoff producing water of high density. Light water enters from the Atlantic Ocean via the Strait of Gibraltar and to a lesser extent from the Black sea at the surface layers and dense saline water is exported by underwater currents. This warm and salty water is injected to the Atlantic Ocean and contributes to the North Atlantic thermohaline circulation (Bethoux *et al*. 1999, Theocharis *et al.* 1999). The main modes of the circulation variability and their response to atmospheric variability are not fully resolved (Tsimplis *et al*. 2006, Hoepffner *et al*. 2006). Therefore continuous monitoring of the circulation patterns at key points in the Mediterranean Sea are essential to assess future changes in the water masses under different warming conditions (Hoepffner *et al.* 2006).

An increase in average temperature in the different levels in the Mediterranean Sea water columns has been found (Bethoux *et al.* 1990, Francour *et al.* 1994). Temperature and salinity data were collected in the northernmost part of the Mediterranean Sea, in the Gulf of Triest (northern Adriatic Sea) over a time period of 1991-2003 by Malacic *et al.* (2006). Temperature at the surface varied with an annual amplitude of 8.1 +- 0.4°C around 16.5°C, while at a depth of 10m it varied with an amplitude of 7.0 +- 0.3°C around 15.5.°C. Summer temperatures at the surface were rising between 0.12 and 0.23°C per year. When the year 2003, which was an extremely dry and hot year, was excluded from the analysis the increase was reduced to 0.07-0.09°C per year. Salinities showed an increase with 0.28-0.34 per year. When excluding the 2003 data, the salinity values showed an increase of 0.22-0.28 per year.

Key message 5

Generally, it can be stated that climate change impacts may be even more severe in semi-enclosed seas than in the open seas and that research is needed for the assessment of climatic effects in the presence of non-climatic stressors (in particular with respect to the high pollution load of the Baltic Sea). Expected impacts will have negative and positive effects on marine productivity.

According to climate change scenarios for the Baltic Sea the prognosis for a decrease of salinity ranges from 8% to 50% and for the increase of the sea surface water from 2 to 4°C.

In the North Sea Region, the prognoses for salinity are variable with expected increases and decreases in different areas of the North Sea. The sea surface temperatures are predicted to rise about 1.6°C to 3.0°C in the Northern North Sea and 3.0°C to 3.9°C in the shallower southern North Sea.

According to climate change scenarios salinity and temperatures will increase in the Mediterranean Sea.

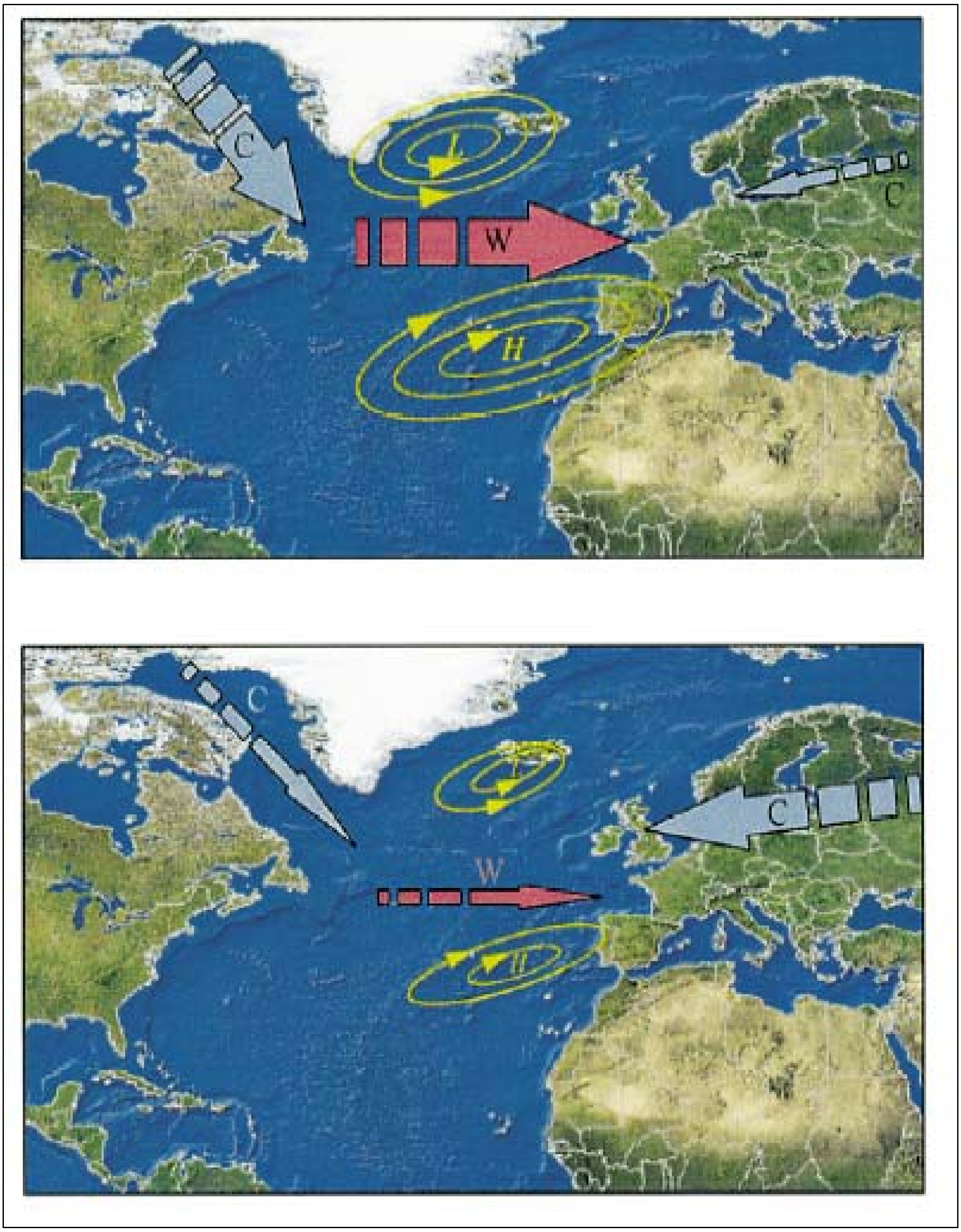
Other relevant literature related to changes of properties of water

Many aspects of the winter climate in the European Union area are strongly influenced by the so called "North Atlantic Oscillation" (NAO), the dominant mode of atmospheric behaviour in the North Atlantic (Hurrell 1995, Hurrell and Dixon 2004). The NAO is an alternation in the pressure difference between the subtropical atmospheric high-pressure zone centred over the Azores and the atmospheric low-pressure zone over Iceland (Hurrell 1995, Ottersen *et al.* 2001). It is the dominant mode of atmospheric behaviour in the North Atlantic sector throughout the year, but it is most pronounced during winter and accounts for more than one-third of the total variance in sea level pressure (SLP) (Cayan 1992; Hurrell 1995).

Several indices for the NAO have been defined, notably those by Rogers (1984) and extended further back in time by Hurrell (1995) and Jones *et al.* (1997). Hurrell's winter (December through March) index of the NAO is based on the difference in normalised SLPs between Lisbon, Portugal, and Stykkisholmur, Iceland, from 1864 through 1995. A high or positive NAO index is characterised by an intense Icelandic Low and a strong Azores High (Figure 10).

The increased pressure differences result in more and stronger winter storms crossing the Atlantic Ocean in a more northerly track. The reduced pressure gradient of the low-index or negative NAO phase leads, on the other hand, to fewer and weaker winter storms crossing on a more west-east pathway. Variability in the direction and magnitude of the westerlies is responsible for interannual and decadal fluctuations in wintertime temperatures and the balance of precipitation and evaporation over land on both sides of the Atlantic Ocean (Rogers 1984; Hurrell 1995). The relationship between the state of the NAO and the temperature, wind and precipitation patterns is particularly strong in northern Europe. The NAO appears to be a good proxy for winter sea surface temperature and wind strength in the North Sea (Ottersen *et al.* 2001).

Figure 10: The North Atlantic Oscillation.



Source: Parsons and Lear 2001.
Notes: Schematic diagram of high NAO index (top) and low NAO index (bottom), where L=Icelandic Low, H=Azores High, C=cold air masses, and W=warm air masses.

The mean sea level variability around Europe has been found to be dominated by the NAO related pressure fields. The water exchange at the Strait of Gibraltar (Gomis *et al.* 2006) and the deep water as well as the upper water variability in temperature and salinity in the Mediterranean have been linked to the NAO (Bethoux *et al*. 1999, Send *et al*. 1999).

The decade of strong gadoid recruitment in the North Sea during the 1960s, the so called "Gadoid outburst" (Cushing 1984), coincided with a period when the NAO showed its most persistent negative phase. These gadoids were four main species (cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*), whiting (*Merlangius merlangius*) and saithe (*Pollachius virens)).* The transports of the North Atlantic Current, the slope current through the Faeroe-Shetland Channel and inflows into the North Sea were all at a long-term low, as were the south westerly winds over the North Sea, which affected both transport and mixing (Parsons & Lear 2001). Furthermore the inflowing water masses and the sea surface temperatures within the North Sea were cold.

In the 1990s when recruitment to the North Sea gadoid stocks was generally low, the NAO was in a persistent and strong positive phase and the regional environmental conditions had changed to the opposite. Sirabella *et al*. (2001) showed that the effect of a positive NAO phase with high sea temperatures was unfavourable for North Sea cod recruitment. Confirmation for this phenomenon was given by analysis of the situation found for Irish Sea cod. Poor recruitment is believed to have resulted from limitation in energy due to the higher metabolic rates during warm years (Planque & Fox 1998).

Alheit & Hagen (1997) studied the fluctuations of herring (*Clupea harengus*) and sardine (*Sardina pilchardus*) populations in the Northeast Atlantic. They were able to examine historical records dating back to the 10th century for herring off the Swedish coast and linked these to changes in atmospheric forcing, i.e. the NAO. They could show that large catches of herring in the English Channel and in the Bay of Biscay coincided with times when the NAO index was negative, hence when severe winters occur in western Europe with extreme cold air and water temperatures and reduced westerly winds. In the inverse situation, during positive phases of the NAO index, when ice cover off Iceland was weak, westerly winds were intensified and there was relatively warm water in the North Sea, English Channel and the Skagerrak. Norwegian spring spawning herring and sardines off southwest England and in the Channel were dominating. This observation led Alheit and Hagen (1997) to conclude that climatic variations govern the alternating of high and low abundance of herring and sardine periods in the Northeast Atlantic. A similar situation has been described for the Pacific Ocean where sardine and anchovy fluctuations have been shown to be associated with large scale changes in ocean temperatures. During warm years sardine dominates the system, whereas during cold years a dramatic increase in anchovy populations occurred (Chavez *et al.* 2003).

There is sufficient evidence to demonstrate that most of the atmospheric circulation variability associated with the NAO arises from internal, nonlinear dynamics of the extra tropical atmosphere. Hurrell *et al* (2006) state, that there is no consensus in the scientific world on the processes that are most likely responsible for the enhanced interannual variability of the NAO. One proposed source of the recent trend in the observed NAO winter index is the strength of the atmospheric circulation in the lower stratosphere on long time scales by reduction in stratospheric ozone and increase in greenhouse gas concentrations. Another theory is that the interaction between the ocean and the atmosphere is important for recent temporal evolution of the NAO (Hurrell et al 2006). Rodwell et al (1999) 'argue that sea surface temperature characteristics are communicated to the atmosphere through evaporation, precipitation and atmospheric-heating processes, leading to changes in temperature, precipitation and storminess over Europe'. Therefore it is possible to try to reconstruct the NAO variability from the knowledge of Atlantic sea surface temperatures. But it is likely that month to month and year to year changes in the phase and amplitude of the NAO will remain largely unpredictable (Hurrell *et al.* 2006).

Key message 6

The North Atlantic Oscillation impacts on the European marine ecosystem. Many aspects of the winter climate in the European area are strongly influenced by the NAO which dominates the atmospheric behaviour in the North Atlantic. Several indices for the NAO have been defined. The NAO affects all marine trophic levels. Recruitment of industrial fish is linked to the NAO index as demonstrated for the gadoid outburst (concerning cod, haddock, whiting and saithe) in the North Sea and for herring and sardine recruitment in the Northeast Atlantic. The NAO is highly unpredictable, although it is possible to reconstruct the NAO from sea surface temperature.

The ex post analyses of the NAO index and the relation to observe impacts on the marine ecosystem may enable to develop models for the prognosis of future impacts.

3.2 Expected effects of climate change on key species

Biological characteristics of industrial key fish species

The study is focused on the European Union's fisheries in the Atlantic and adjacent Seas. Therefore the literature review concentrates on key fish species with particular relevance for European fisheries in the Atlantic, the North Sea, the Mediterranean Sea and the Baltic Sea. In order to get an overview of the individual environmental requirements of the relevant fish species, the biological characteristics have been identified for the following industrial key fish species:

Table 5: Selection of key species and their area of relevance in the study scope

Key species	Area of relevance in the study scope
Atlantic herring *(Clupea harengus)*	North East Atlantic, North Sea, Baltic Sea
Sprat *(Sprattus sprattus)*	North East Atlantic, North Sea, Baltic Sea, Mediterranean
European pilchard *(Sardina pilchardus)*	North East Atlantic, Mediterranean
European anchovy *(Engraulis encrasicolus)*	North East Atlantic, Mediterranean
Atlantic mackerel *(Scomber scombrus)*	North East Atlantic
Northern bluefin tuna *(Thunnus thynnus)*	Atlantic, Mediterranean
Blue whiting *(Micromesistius poutassou)*	North Sea
Atlantic cod *(Gadus morhua)*	North East Atlantic, North Sea, Baltic Sea
Norway pout *(Trisopterus esmarkii)*	North East Atlantic, North Sea
European hake *(Merluccius merluccius)*	North East Atlantic, North Sea, Mediterranean
Great sandeel *(Hyperoplus lanceolatus)*	North Sea
Lesser sandeel *(Ammodytes marinus)*	North Sea
Haddock (*Melanogrammus aeglefinus*)	North East Atlantic
Saithe (*Pollachius virens*)	North East Atlantic
European plaice *(Pleuronecta platessa)*	North East Atlantic, North Sea
Round sardinella *(Sardinella aurita)*	Mediterranean
Atlantic horse mackerel *(Trachurus trachurus)*	North East Atlantic, Mediterranean
Skipjack tuna *(Katsuwonus pelamis)*	Atlantic, Mediterranean
Yellowfin tuna *(Thunnus albacares)*	Atlantic, Mediterranean

Source: Based on Fröse and Pauly 2007.

Although a variety of abiotic and biotic characteristics of key species are affected by climate change, temperature is a key issue that controls processes from cell to whole organisms.
One goal of integrative biology is to understand how temperature affects physiological mechanisms at all levels of biological organisation to allow predictions of how global warming could affect animal performance and population dynamics (Harrods *et al*. 2007). Since fish are thermal conformers (Jobling 1997) their body temperature is effectively that of the surrounding water. Temperature affects physiological processes ranging from protein damage to membrane fluidity and organ function (Hochachka & Somero 2002) by determining the individuals enzymatic, physiological and biochemical rates (Clarke, 1993; Coutant 1987; Regier *et al.* 1990, Pörtner & Knust 2007).

Some fish are capable of detecting and responding to extremely small temperature variations (Brown 2003). Fish tend to select their thermal habitats to maximise their growth rate (Magnuson *et al.* 1979) and are able to optimise physiological, ecological, and reproductive performance (Coutant, 1987). Energetic costs for thermal adaptation processes and general energy budget will have an effect on and shape the width of the thermal window a fish can tolerate and will influence growth performance, development, fecundity and recruitment (Pörtner & Knust 2007), thereby influencing the fish's ecology and physiology (Brett 1956; Ferguson 1958; Fry 1971; Magnuson *et al.* 1979).

If fish encounter habitats with unsuitable thermal regimes, they respond behaviourally and attempt to move into areas closer to their preferred temperature with consequences for their biogeography([46]), since they lack the physiological ability to regulate their body temperature (Jobling, 1997; Sims *et al.* 2006). When temperature thresholds are exceeded, immune systems of stressed individuals can be weakened leading to disease outbreaks (Harvell *et al*. 1999).

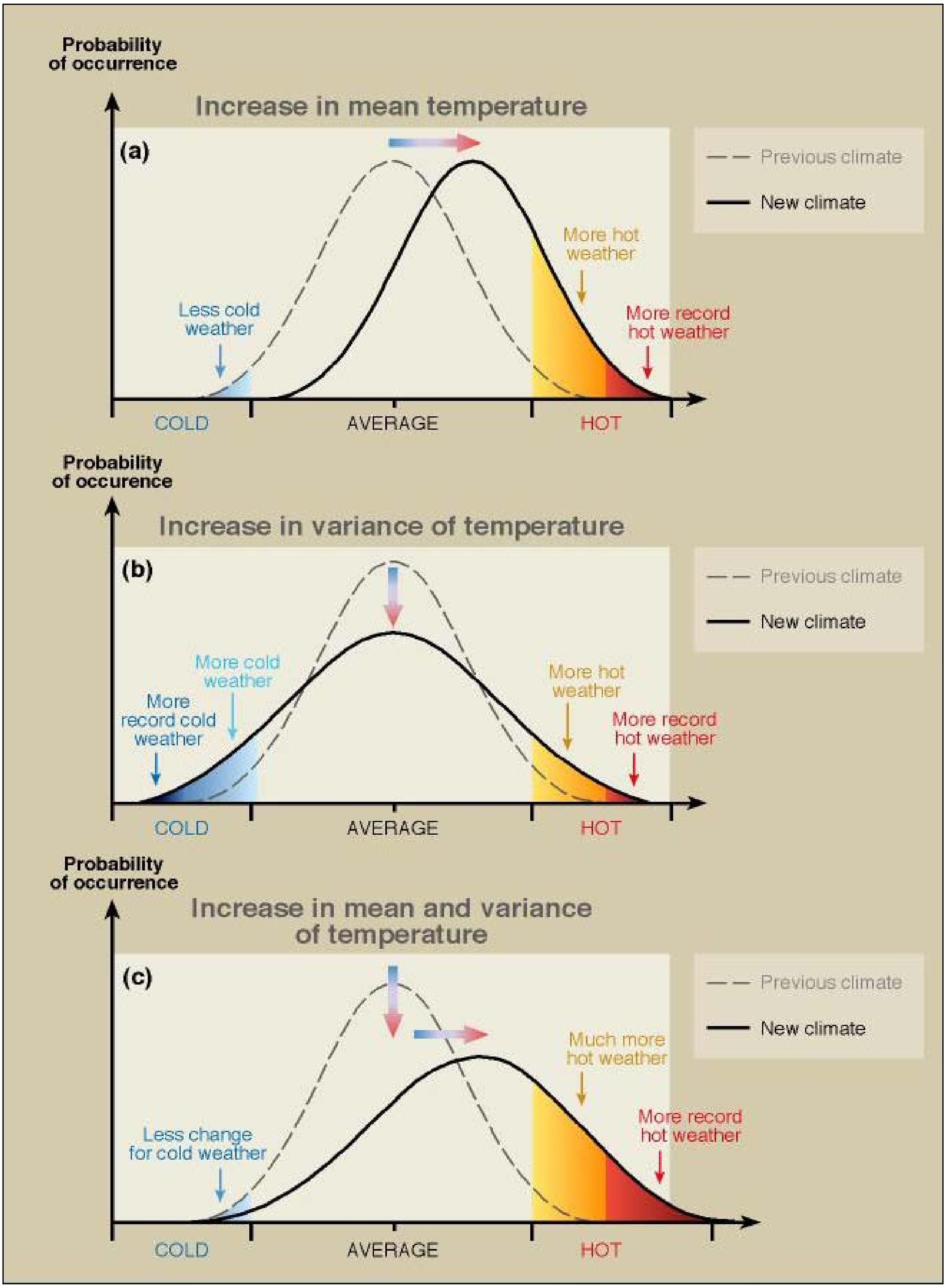
The thermal niche of a fish species can be defined by lethal, controlling, and directive criteria (Fry, 1971). For example, extreme temperatures may be lethal if certain limits are exceeded (Jobling 1981), but temperature also directs behaviour (Reynolds, 1977) and controls individual physiology (Regier *et al.* 1990). Predicting the effects of temperature change on fish is difficult due to the huge variation in possible responses that individuals can exhibit, and the potentially confounding influence of many other physiological or environmental factors (Burton, 1979; Fry, 1971).

Since temperature has such an important influence on the individual biology of a fish, it will also have ecological consequences on fish at population (*e.g.* Mills & Mann, 1985) and community levels (*e.g.* Persson, 1986; Southward *et al.* 1988).

Climate change can lead to temperature changes resulting in a change in the mean temperature or in increased variability of temperature. Maximum and minimum temperatures could have a far greater effect on the biotic community than the change in the mean (IPCC report 2001 Figure 11).

([46]) Describes the distribution of organisms on earth and analyzes the causes of the geographical distribution of living and extinct taxa;

Figure 11: Effects of Extreme Temperatures.



Source: IPCC 2001 synthesis report.

Notes: Schematic diagrams showing the effects on extreme temperatures when (a) the mean increases, leading to more record hot weather, (b) the variance increases, and (c) when both the mean and variance increase, leading to much more record hot weather.

The key industrial, or economically important, species for the EU fisheries cover a range of different life history traits, from pelagic to demersal([47]) species, from temperate to subtropical habitat. In order to present the basic biological characteristics of the industrial key fish species the largest fish database, FishBase (Fröse and Pauly, 2007) was used. The following information has been gathered for each species and is compiled in Annex 1-1:

- geographical distribution
- maximum size and age
- environmental characteristics (water zone, type an depth)
- temperature range
- minimum population doubling time.

Detailed information was corrected or added if necessary. Maps of the known distribution were taken from Muus and Nielsen (1999).

Key message 7

Changes in temperature can lead to shifts of fish populations, the invasion of alien species and disappearance of species. Temperature is a fundamental component of the niche of fish. Fish tend to select thermal habitats that maximise their growth rate. However, predicting the effects of temperature change on fish is difficult. In addition to temperature, food availability and suitable spawning grounds determine the large scale distribution of fish.

Abundance and distribution of existing and new populations

An increase in water temperature influences the life of marine organisms both directly and indirectly. A direct physiological impact is seen, when the limit of the tolerance range for a species is under-run or exceeded. An indirect effect of increasing water temperature is observed when previously temporally and spatially available food organisms are no longer present due to changes in the species assemblage of an ecosystem caused by the temperature change.

Temperature, food availability and suitable spawning grounds determine the large scale distribution of fish. Because fish species or stocks prefer a specific temperature range, an expansion or contraction of the distribution range of a species often coincides with long term changes in temperature. These changes are most evident near the northern or southern boundaries of the species range. Warming has been shown to result in a distributional shift northwards and cooling draws species southwards (Rose 2005).

The effects of climate change on the phenology, abundance and distribution of terrestrial taxa has been well documented (Parmesan, 2006; Parmesan & Yohe, 2003; Root *et al.* 2003; Walther *et al.* 2002). In a meta-analysis, Parmesan & Yohe (2003) calculated that spring events (*e.g.* bird-nesting, and frog-breeding) had advanced, on average by 2.3 days per decade and that diverse taxa had undergone significant range shifts towards the poles, averaging 6.1 km per decade.

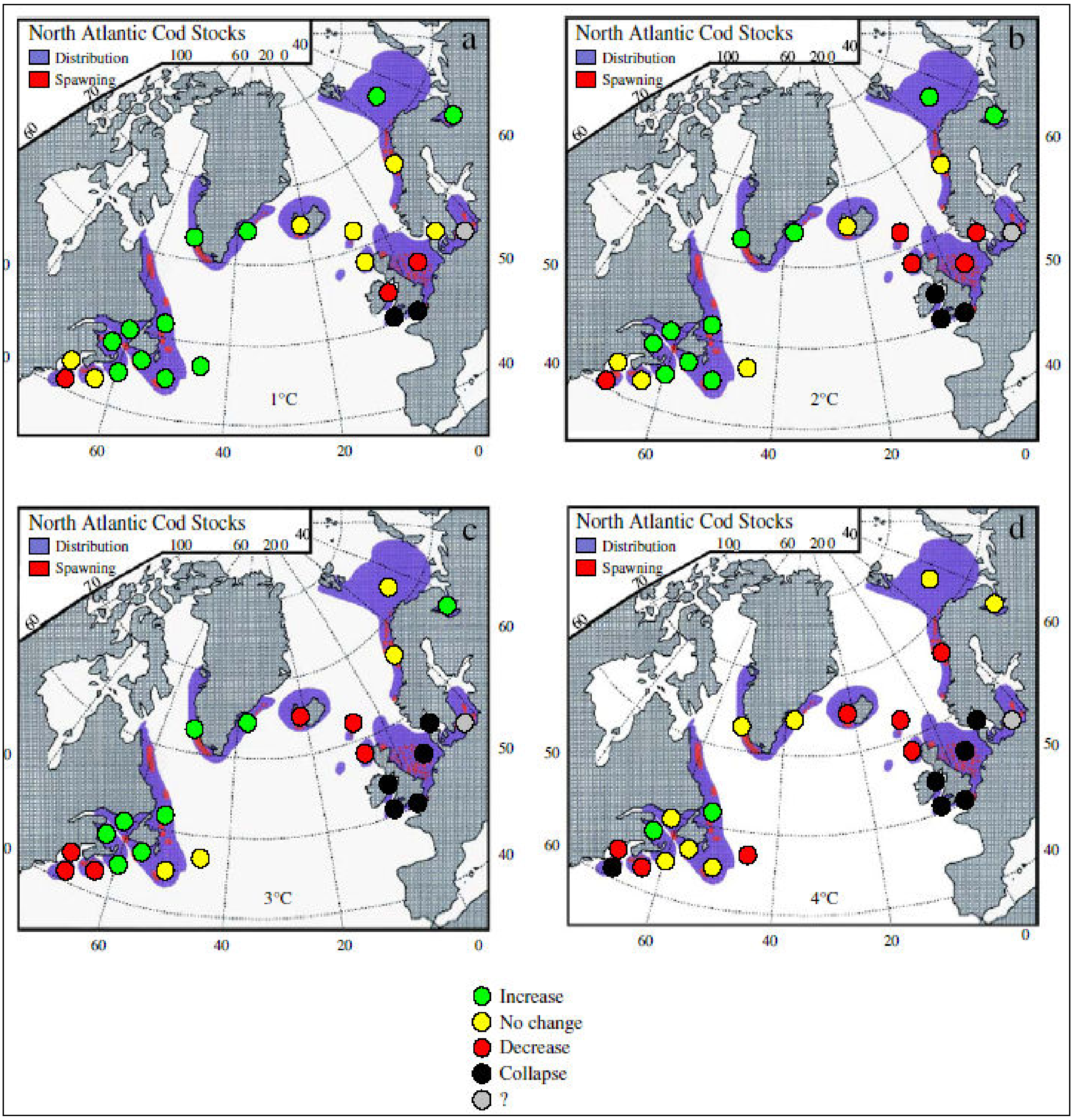
To analyse the effect on fish, Parmesan and Yohe (2003) have used data by Holbrook *et al.* (1997) and Southward *et al.* (1995) who had analysed a time series of 70 years in the English Channel. They found that the abundance and distribution of fish and zooplankton changed in relation to a rise in sea temperature. Warm water species increased in 2 to 3 orders of magnitude in abundance in periods of rising sea temperature with latitudinal shifts of up to 120 miles northwards. Holbrook et al. (1997) also analysed a fish assemblage in a temperate reef and

([47]) Living in close relation with the bottom and depending on it.

found a close connection to a shift in climate. The species richness declined and the composition shifted from a dominance of northern to southern species.

Perry *et al.* (2005) analyzed shifts in boundaries using more than 60 different North Sea fish species. The main findings were a shift of boundaries of half of the species with a northward trend except for one species, the Norway pout, which moved slightly southwards to colder water to avoid the North Atlantic current transporting warm water to the northern North Sea. The most affected species was the blue whiting with a northward shift of its southern boundary of 816 km. However not every species reacted with a latitudinal offset. Plaice for example only moved to deeper, colder water. Hawkins *et al.* (2003) also showed a shift in the pelagic species Atlantic herring, European pilchard and Atlantic mackerel.

Figure 12: Impact of Temperature on Cod Stocks.



Source: Drinkwater 2005.

Notes: Expected changes in the abundance of the cod stocks with a temperature increase of (a) 1(C, (b) 2(C, (c) 3(C, and (d) 4(C above current levels.

Trawl data from Scottish research vessels dating from January 1925 show that catches of the warm water pelagic species, anchovy (*Engraulis encrasicolus*), sardine (*Sardina pilchardus*) and red mullet, species normally only rare in Northern Europe, increased suddenly after 1995 (Beare *et al*. 2004). The authors believe that these changes are related to rising sea temperatures although the exact causal mechanism is not clear.

Since all these species are heavily exploited, the influence of water warming on abundance fluctuations remain uncertain and speculative and a distinction of direct causal relations between environmental temperature and distribution pattern is difficult (Jensen 2003). Nevertheless, Maravelia *et al.* (1995) as well as Misund *et al.* (1998) showed the influence of water temperature and salinity on the migration of herring, but both argue that the influence could also be indirect through a shift in the prey availability. Importantly, the analysis by Perry *et al*. (2005) showed similar results for both exploited and non-exploited demersal and bentho-pelagic species indicating that the reaction to the increase in temperature was not affected by the species being exploited or not.

Recently Hannesson (2007) analyzed the catches of cod, herring, mackerel, anchovy and sardine in the North Sea and the Norwegian Sea. He stated that the heavy fishing pressure on herring and cod in the North Sea made it difficult to see an effect of warming on the abundance of both species. A sharp increase in mackerel landings in the late 1960s was related to a shift in fishing technology. Nevertheless a following increase in the 1970s was positively related to increasing water temperature. For anchovy no correlation could be detected, whereas for sardine the increase could be related to water temperature. The warmer water temperature also seemed to have a positive effect on the recruitment of cod in Norwegian waters, but a negative one for the North Sea. A northward migration of cod was rejected due to a missing increase in catch in the Norwegian Sea. Arnott and Ruxton (2002) predict that the southern limit of the sandeel population in the North Sea should shift northwards if conditions become warmer.

One of the few examples of a prediction on how cod stocks might behave in relation to increased temperature has been made by Drinkwater (2005, Figure 12). He coupled current knowledge about the impact of climate variability on Atlantic cod (*Gadus morhua*) with predictions of future climate change to predict the shift in distribution of cod in relation to increase in water temperature and chose cod for his analysis, since cod is one of the most studied species in the North Atlantic and the information about life history, and biology of the species is greater than the information we have on most other fish species.

Cod are not much observed above annual mean bottom temperatures of 12°C (Dutil & Brander 2003). If bottom temperature increases over 12°C the cod will disappear by moving into cooler waters or because of mortality. The anticipated increase in the mean annual temperature by the year 2100 in the continental shelf waters occupied by different cod stocks will be between 2-6°C with the highest increased predicted for the North East Arctic cod. Cod in the North Sea will experience a 2-3°C increase in temperature, cod in the Baltic Sea might have to cope with an increase of 3-4°C. Today cod in the North Sea have reached their thermal tolerance limits resulting in the population moving northwards (Drinkwater 2005, Figure 12).

The relative abundance of non-migratory eelpout (*Zoarces viviparus*) in the North sea has decreased in relation to warming in a data set from 1954-1989 analysed by Pörtner & Knust (2007) reflecting a higher mortality in hot summers. Since these are non-migratory species, they cannot escape when temperature gets beyond their tolerance threshold and respond with mortality.

Genner *et al*. (2004) examined the effects of regional climatic change on fish assemblages from two independent data sets from the English Channel (1913-2002) and the Bristol Channel (1981-2002). They could show that climatic change had dramatic effect on community composition with northwards shifts occurring. Each fish assemblage contained a subset of dominant species whose abundances were strongly linked to annual mean sea-surface temperature. Species' latitudinal ranges didn't result in being good predictors of species-level responses, since the same species did not show congruent trends between sites. Therefore Genner *et al.* (2004) suggest that within a region, populations of the same species may respond differently to climatic change, possibly responding to additional local environmental determinants, interspecific([48]) ecological interactions and dispersal capacity. This will make species-level responses difficult to predict within geographically differentiated communities.

Several catches of warm fish species in the "cold biota" of the Mediterranean Sea have been found (Francour *et al.* 1994). Fish species coming from the eastern and southern Mediterranean have appeared in the Northern areas of the Tyrrhenian Sea (Gulf of Lyon and Corsica). Conversely the cold species like sprat (*Sprattus sprattus*) and Atlantic mackerel (*Scomber scombrus*), which used to be relatively abundant in the northern areas of the Mediterranean (North Adriatic Sea and Gulf of Lyon), have become very scarce or disappeared (Bombace 2001, Dulcic *et al.* 1999). In the 1990-1995 when sea surface temperature anomalies were +0.30°C in the Adriatic Sea, most of the new occurrences of species, were observed. 11 subtropical and tropical thermophilic species have occurred and have increased in the Adriatic Sea over the last 25 years (Dulcic *et al.* 1999).

Key message 8

Direct and indirect climate effects can lead to a shift of fish populations, the invasion of alien species and even to the disappearance of species. In several studies the abundance and distribution of fish and zooplankton related to a rise in sea temperature was observed.

Many industrial fish species are directly plankton dependent. Plankton-feeding fish species, in particular sardine and anchovies, show strong natural fluctuations with climate variations. Investigations related to climatic warming indicated shifts from a dominance of northern species to a dominance of southern species. Shifts in boundaries using more than 60 different North Sea fish species showed a shift of boundaries of half of the species (exploited and non-exploited) with a northward trend. Some species may have reached their tolerance limits, such as cod in the North Sea, resulting in northwards movement of their populations. The decrease in cod was correlated with changed species assemblages, stock decline and smaller average body size of the zooplankton. This can probably be attributed to climate change. The shift of populations (e.g. as demonstrated for the Atlantic cod) can lead to the complete loss of stocks at the regional level.

Warm fish species invade "cold" ecosystems. Several warm fish species have invaded "cold" ecosystems and cold species which used to be relatively abundant in "warm" ecosystems have become very scarce or have disappeared. E.g. sprat and mackerel have become very scarce or disappeared from the Mediterranean Sea.

Shifts have been shown in many more cases. However, since the considered species are often heavily exploited, the establishment of direct causal relationships between temperature and distribution pattern is difficult. Reliable prognoses on the probable development of fish stocks due to climate change effects are only possible for some intensively investigated species (e.g. Atlantic cod). Separation from other impact factors is difficult. Research is needed.

([48]) Between different species, e.g. competition.

Geographical range extensions or distribution of fish populations

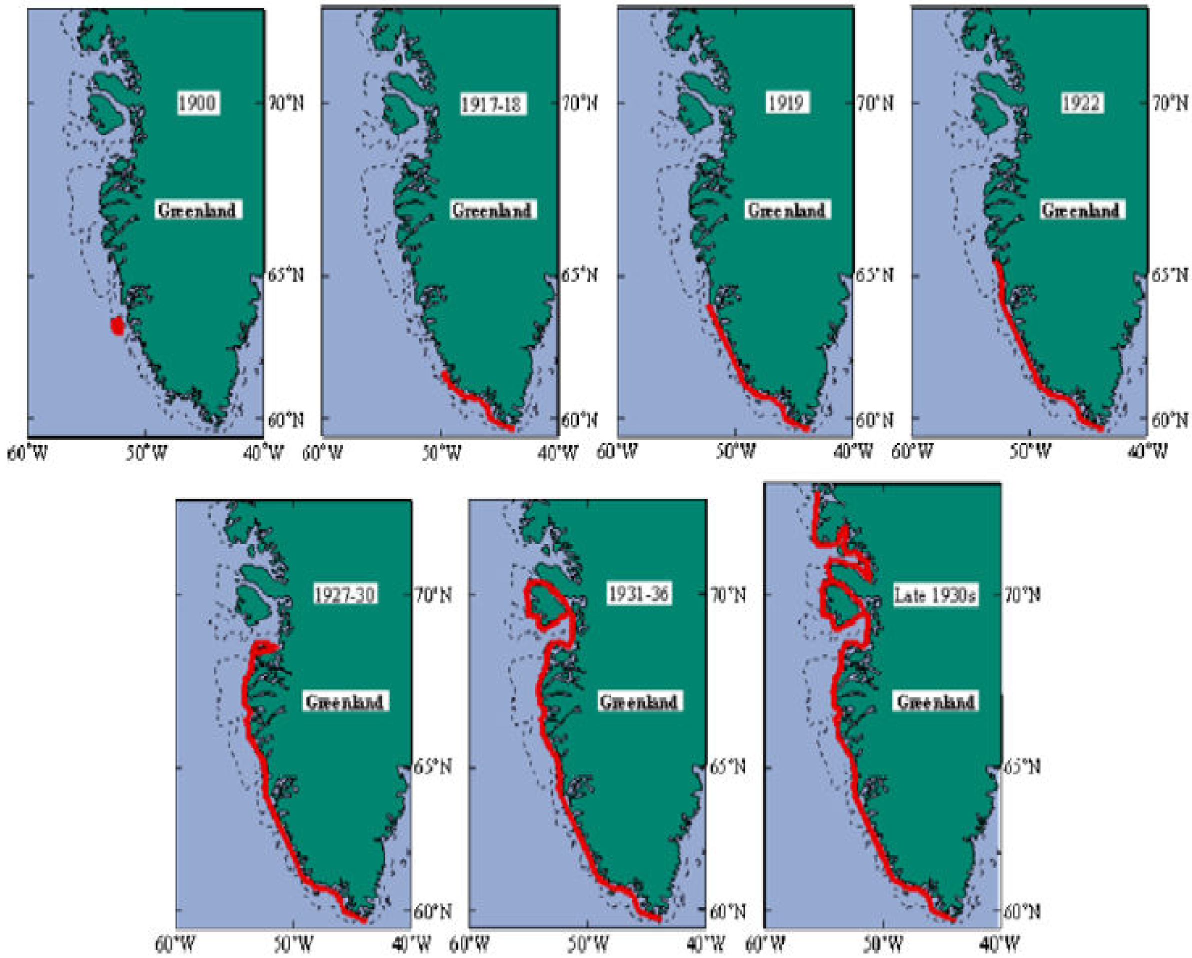
Changes in species geographical range extension will depend on "Bioclimatic envelopes" or "Climatic spaces", which are determined through techniques that correlate current species distribution with climate variables or through an understanding of the individual's physiological response to climate change (Pearson & Dawson 2003). It is assumed that changing climate has a direct influence on survivorship, dispersal, fecundity and behaviour of individuals and will directly transfer to changes in abundance and distribution (Walther *et al*. 2002). To be able to predict the movement of a species we need to have knowledge about a species climatic envelope and apply this information in future climate change scenarios. This will then serve as the basis to estimate the potential redistribution of a species.

The validity of such a bioclimatic envelope approach([49]) has been questioned since many factors other than climate play an important part in determining species distribution and the dynamics of these changes. Biotic interactions, evolutionary change and dispersal ability have to be taken into consideration. The bioclimatic envelope model therefore can only provide an approximation as to the potential impact of climate change. It has to be kept in mind that the complexity of the natural system presents fundamental limits to modelling strategies. A weakness of correlative approaches is that these correlations might not apply in the future as the conditions, especially the interspecies relationships can change (Pearson & Dawson 2003).

In order to learn from past trends and make probability statements into the future Drinkwater (2006) reanalysed the effects of a dramatic warming of air and ocean temperatures in the Northern North Atlantic and high Arctic in the 1920s and 1930s. Higher recruitment and growth led to increased biomass of commercially important species such as cod and herring in many regions in the North Atlantic. On the other hand colder water species like capelin no longer migrated as far south. An expansion of Atlantic cod and halibut (*Hippoglossus hippoglossus*) distribution along the west coast of Greenland in response to the changes in the ocean climate was documented (Jensen 1939, cited in Drinkwater 2006, Figure 13). The explanations for the sudden appearance of cod are believed to be due to a combination of the effect of larval drift from Iceland because of the increased flow of the Irminger Current and a better survival of larvae once they reached the Greenland waters.

([49]) Determined through techniques that correlate current species distribution with climate variables or through an understanding of the individual's physiological response to climate change.

Figure 13: Impact of Warming Periods on Cod Distribution.



Source: Drinkwater 2006.
Notes: The cod distributions (in red) along West Greenland from 1900 to the late 1930s showing the northward extension during the warming period.

Haddock catches off West Greenland provide additional evidence of increased larval transport, since this species does not spawn west of Greenland and must have originated from Iceland (Dickson & Brander 1993). During these warm periods in the 1920s and 1930s spotted catfish (*Anarchichas minor*) herring (*Clupea harengus*) as well as mussels (*Mytilus edulis*) and starfish (*Asterias*) extended northwards and reproduced successfully in areas north of their previous range. Migration patterns of warmer water species also changed leading to earlier arrivals and later departures. These studies indicate that increase in temperature not only made new areas attractive for fish but that the change in climate also led to a change in current systems which affected the larval transport routes.

Based on increased phytoplankton and zooplankton production in several areas, bottom up processes likely were the primary causes of these changes. By studying the response of the increase in temperature in the 1920s and 1930s and comparing with today, one can see that several of the observed changes that occurred are repeating themselves. As temperature declined in the North Atlantic during the 1960s the ecological situation returned to its previous state. In some regions however, new regimes became established, e.g. the West Greenland shrimp biomass increased and became the dominant economic fishery, replacing cod (Drinkwater 2006). Similar trends have been observed for the cod fishery in Nova Scotia, Canada, where the commercial fishery which was dominated by cod is now dominated by shrimp and snow crab. Several management measures (fishing closure, new fishing design to save the cod) to reverse the trend and to restore the system to its earlier state have failed. It remains an open question whether the recent changes are reversible (Frank *et al.* 2005).

Key message 9

Climate change influences abundance and distribution of industrial fish. Changing climate has a direct influence on survivorship, dispersal, fertility and behaviour of individuals and thus on abundance and distribution. Prognoses are difficult since many factors other than climate impacts play an important part in determining species distribution and the dynamics of these changes. Changes in the geographical range extension have contributed to an increased productivity of cod and haddock around Greenland. This has been a response to dramatic warming in 1920 to 1930. The primary cause for these changes were bottom up processes due to increased phyto- and zooplankton production.

Growing seasons, winter mortality and growth rates

The environment has an important effect on growth of fish. Brander (1994, 1995) was able to show that the mean bottom temperatures account for 90% of the observed difference in growth rate between different Atlantic cod stocks in the North Atlantic with cod from warmer temperatures experiencing faster growth rates. Temperature not only accounted for differences in growth rates between cod stocks but also accounted for year to year changes within a stock (Brander 2001) and hence could determine the surplus production of the cod stocks (Dutil & Brander 2003).

In order to examine the likely impacts of climate change on fish population it is necessary to couple large scale climate models to fisheries population simulations. Clark *et al.* (2003) have used projections from the Hadley General Circulation Model from the period 2000 - 2050 to estimate the likely effects of climate change on North Sea cod populations. The effect of temperature was incorporated through a dome shape temperature growth relationship for the different size classes using the parameters given by Bjornsson & Steinarsson (2002). Mean North Sea bottom temperature for the period 1998-2000 was about 8.67°C. Since the optima for cod growth is at a temperature of around 8.5°C (Bjornsson & Steinarsson 2002), increase in environmental temperature above those currently observed in the North Sea will not lead to increased growth and will not increase recruitment or spawning stock biomass (SSB) (Clark *et al.* 2003).

Although Clark *et al.* (2003) stress that simulations developed for the North Sea cod are based on relatively simplistic approaches and omit many other potentially important processes, their results can demonstrate that the inclusion of environmental factors in population models can alter the perception of how fish populations will behave. These simulations can provide management advice and show that the inclusion of environmental effects will become increasingly important (Jurado-Molina & Livingstone 2002).

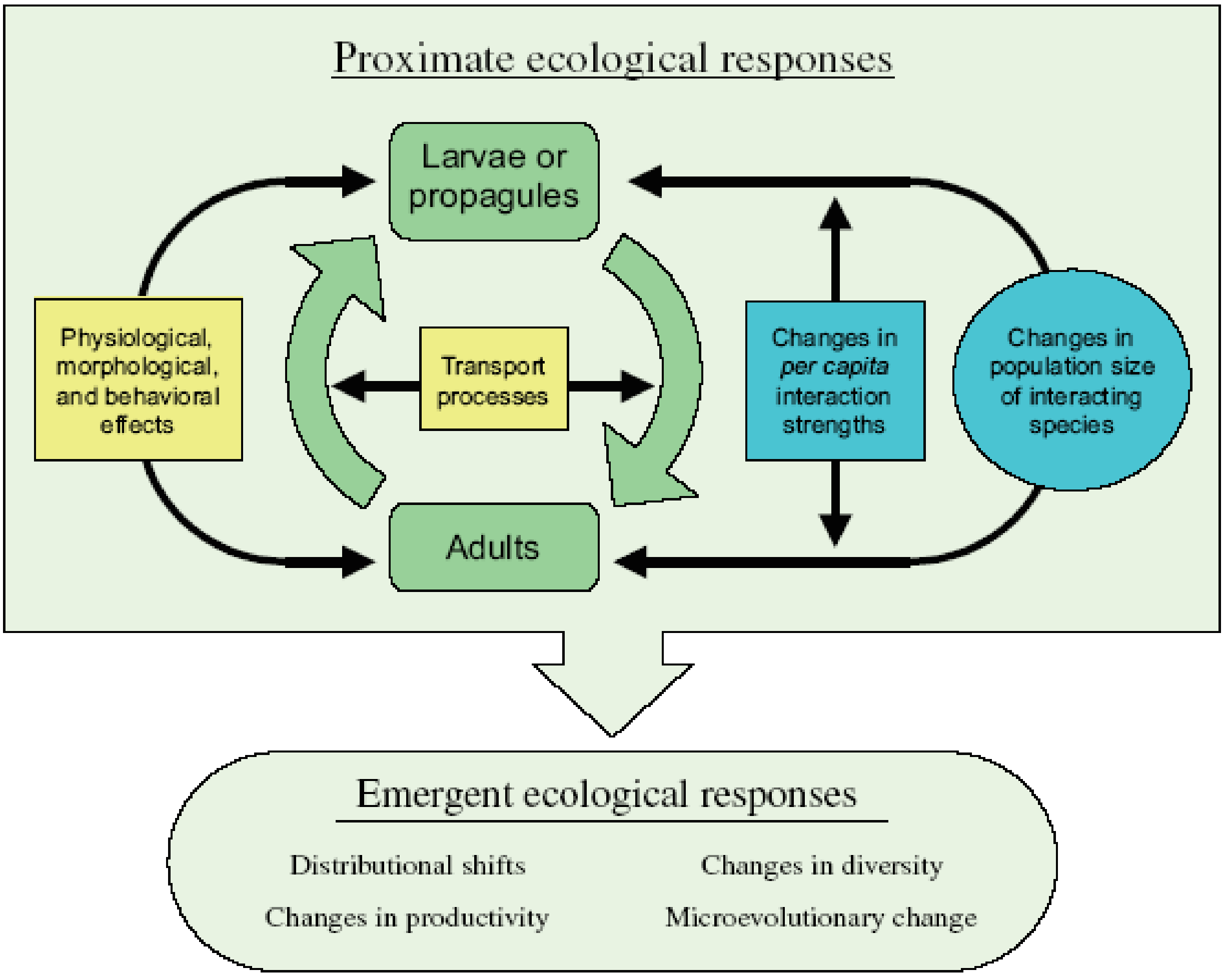
Key message 10

Mean bottom temperatures can be crucial for the growth rate of a fish stock. According to simplistic simulations developed for the North Sea cod increasing bottom temperatures are expected to have a negative impact on the growth rate of cod. Such approaches demonstrate that the inclusion of environmental factors in fish population models can alter the prognosis on how populations will behave. Simulations can provide management advice and show that the inclusion of environmental effects may become increasingly important in fish stock management.

Reproductive patterns, migration routes and ecosystem relationships

The direct effects of climate change impact on the performance of individuals at various stages in their life history, via changes in physiology, morphology and behaviour (Harley *et al*. 2006). Climate impacts also occur at the population level via changes in the transport processes that influence dispersal and recruitment. Community level effects are mediated by interacting species and include climate driven changes in both the abundance and interaction strength of the species (Figure 14).

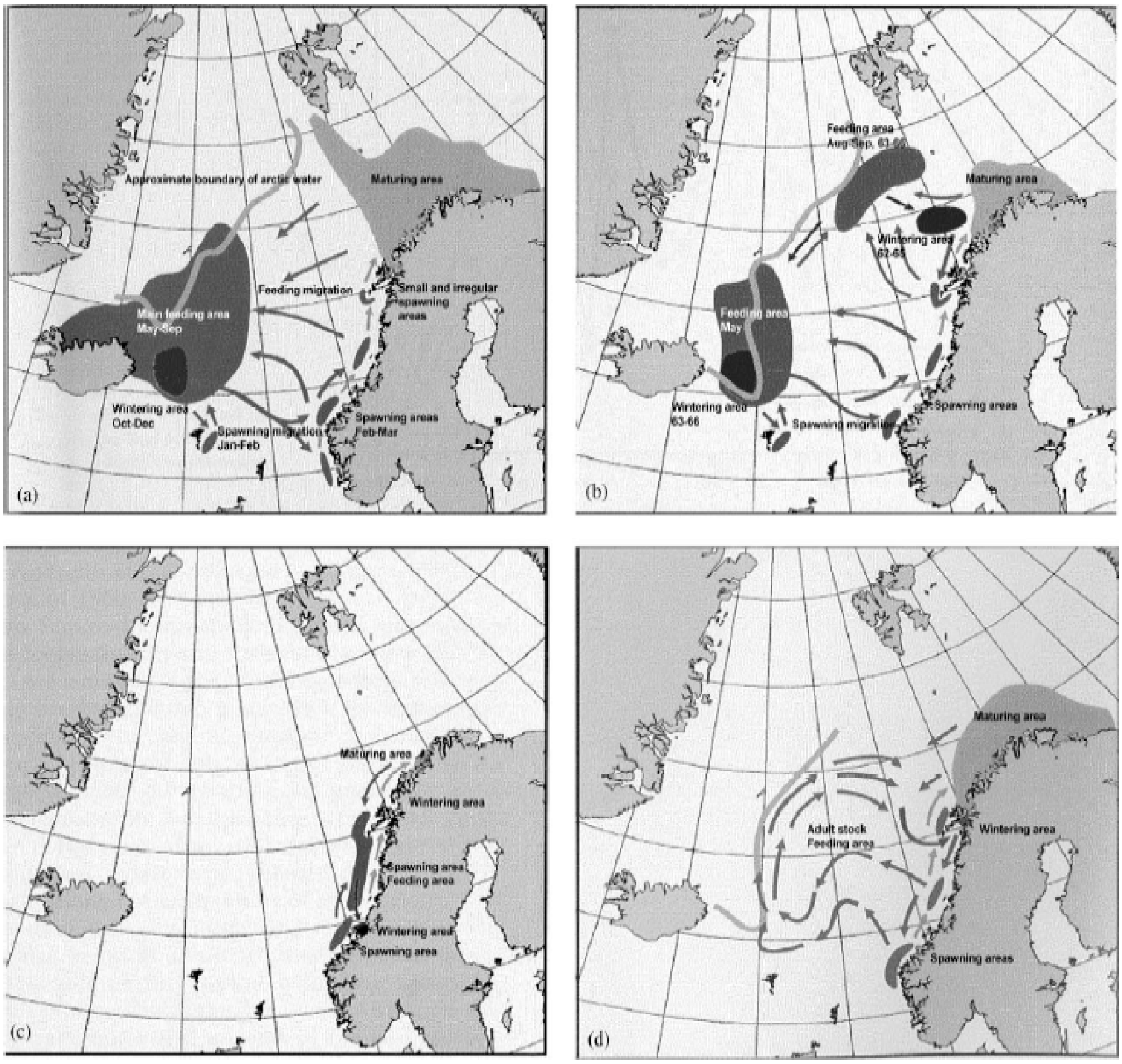
Figure 14: Potential Ecological Responses to Climate Change.



Source: Harley et al. 2006.
Notes: The life cycle of a generic marine species is shown in green. Abiotic changes in the environment have direct impacts (yellow boxes) on dispersal and recruitment, and on individual performance at various stages in the life cycle. Additional effects are felt at the community level via changes in the population size and per capita effects of interacting species (in blue). The proximate ecological effects of climate change thus include shifts in the performance of individuals, the dynamics of populations, and the structure of communities. Taken together, these proximate effects lead to emergent patterns such as changes in species distributions, biodiversity, productivity, and microevolutionary processes.

Trade-offs between current and future reproduction, growth and survival imply that participation in the spawning will only pay off in terms of fitness, when fish are sufficiently large and in sufficiently good condition. Skip spawning (= not participating in the spawning process) was observed in Norwegian spring spawning herring (Engelhard & Heino 2006) and found to be not only related to fish size and condition but also to climatic factors and sea surface temperatures. Engelhardt & Heino (2006) found better feeding conditions for herring, better survival and a higher participation in reproduction in colder years when *C. finmarchicus*, the dominant herring food source was more abundant (Fromentin & Planque 1996). Climatically driven increase in water temperature leading to skipped spawning([50]) therefore can have an indirect effect on the population's reproductive potential and could be relevant for the commercial herring fisheries in the Barents Sea. Moreover, Sissener and Bjoerndal (2006) found evidence for change in the migration behaviour of Norwegian spring spawning herring related to climatic influences (Figure 15).

Figure 15: Impact of Climate Change on Migration Behaviour.



Source: Vilhjalmsson 1997, Drinkwater 2006.
Notes: (a) The migration pattern for Norwegian spring-spawning herring, 1950;
(b) the migration pattern for Norwegian spring-spawning herring 1965–66;
(c) The migration pattern for Norwegian spring-spawning herring 1972–86;
(d) The migration pattern for Norwegian spring-spawning herring 1995–99.

The migratory pattern of Norwegian spring spawning herring consist of four phases, spawning, nursery, feeding and overwintering. In January the adult herring start their migration to the

([50]) A fish that already participated in reproduction, but skips one or more seasons.

spawning grounds, spawning takes place from February to April. After spawning the adults migrate to the feeding grounds, while the currents carry the larvae to the nursery grounds. The feeding period is over by the middle of November and the adult stocks migrate to the wintering area. These phases are usually stable, but the geographic locations have shifted over time (Sissener & Bjorndal 2005). The boundary of the Arctic water has an influence on the migration pattern of the herring, since they tend to stay east of that boundary line.

Fish either return to the area where they were born or choose a spawning area based on the environmental conditions which favour the survival chances for their offspring. During cold periods the reproductive activity of blue fin tuna seems to be restricted to the traditional permanent spawning grounds in the Mediterranean. Since the last stages of gonad maturation in blue fin tuna occur within a short period of time and under the control of temperature (Medina *et al.* 2002) suitable temperatures can induce the last stages of gametogenesis and thus reproduction, and could be a reason why more locations along the migration routes of the tuna could be suitable for spawning as water temperature increases. This would mean that the blue fin tuna population could also reproduce outside of its traditional spawning grounds during warm periods. Increased spawning outside traditional grounds may lead to decreased recruitment within traditional spawning grounds. Data analysed by Ravier & Fromentin (2004) suggest this kind of ‘opportunistic homing’ which combines the ‘natal homing’ hypothesis with the opportunistic reproductive strategy for blue fin tuna.

Key message 11

As demonstrated by several examples, **climate change can have an indirect positive or negative effect on reproduction success of industrial fish.** In the case of the Norwegian spring spawning herring a climatically driven increase in water temperature has the effect that fish populations do not participate in the usual spawning process. This has an indirect effect on the reproductive potential and directly impacts on commercial fisheries (loss of stocks). Blue fin tuna could also reproduce outside of its traditional spawning grounds during warm periods. This would have a positive effect on the productivity of the blue fin tuna stock.

Local shifts in production centres and mixes of species; geographical displacements and internal changes in ecosystems

Ecosystem regime shifts have been shown to be linked to climate forcing but can also occur due to anthropogenic forcing such as heavy fishing or pollution (Steele 2004, Collie *et al*. 2004, Chavez *et al.* 2003, Frank *et al*. 2005). A regime shift in marine ecology is “a persistent radical shift in typical levels of abundance or productivity of multiple important components of the marine biological community structure”. It occurs at multiple trophic levels and on a geographical scale that is at least regional in extent. Distributional shifts are often characteristic for a regime shift (Drinkwater 2006).

Changes in temperature and other abiotic factors are likely to result in changes in interspecific interactions which will further influence the response of fish and other taxa to climatic change (Davis *et al.* 1998). As individual taxa will respond differently to climate change, there is clear scope for shifts in community level interactions following climate change (*e.g.* predator-prey relationships, competition and parasitism) to influence the ecology of fish and other taxa (Harley *et al.* 2006). Climate change has the potential to affect fish at several levels: *i.e.*, cellular, individual, life-stage, population, species, community and ecosystem. Harley *et al*. (2006) stress the importance of conducting studies on population and community levels, since direct climatic effects on individuals do not translate directly into changes in distribution and abundance.
The sensitivity of the Baltic marine ecosystem to temperature variations has been demonstrated. Northern Baltic annual peaks of the most abundant cladoceran species were found to co-vary

with surface temperatures. Higher temperatures during the 1990s in combination with lower salinity were associated with a shift in dominance within the open sea copepod community from *Pseudocalanus* to *Acartia* (Möllmann *et al.* 2003). Increased production and survival rates were found for sprat and herring populations co-occurring with high temperatures and high NAO values. The decrease in salinity observed in the late 1970s in the Northern Baltic Sea was reflected in the decline in the large neritic copepod species and an increase in freshwater cladocerans([51]). In contrast temperature sensitive species (e.g. *Acartia*) have increased their population size. The decrease in herring and sprat growth has been related to a salinity-mediated change in the copepod community. The top predator in the pelagic food chain in the Baltic Sea, the cod which usually regulates the sprat and herring stock has decreased. In addition cod eggs need a minimum salinity for buoyancy of 11.5 psu, which they usually find in the halocline([52]) regions in the deep Baltic basins (Wieland *et al.* 1994). Due to low salinity and also low oxygen concentrations in these deep basins cod eggs are frequently exposed to lethal oxygen conditions and survival of cod offspring and following recruitment will be affected. Enhanced sprat reproductive success induced a switch from a cod-dominated system to a sprat dominated system indicating a regime shift (Köster *et al.* 2005, Alheit *et al.* 2005). Landings of anchovies and sardines and the productivity in the Pacific Ocean have varied over the last 50 years. In the mid 1970s the Pacific changed from a cool anchovy regime to a warm sardine regime with a switch to a cool anchovy regime occurring again in the middle to the late 1990s. (Chavez *et al.* 2003).

Key message 12

Climate change has the potential to affect fish at several levels: i.e., cellular, individual, life-stage, population, species, community and ecosystem. Changes in temperature and other abiotic factors are likely to result in changes in interactions between species which will further influence the response of fish and other organisms to climatic change.

Climate change causes shifts of industrial fish populations. Several examples for temperature or salinity induced changes of interactions (food organisms, predators, competitors, reproduction) result in the shift of populations. These examples can be used to explain some interactions and internal changes in ecosystems. However there is a need to conduct studies on population and community levels, since direct climatic effects on individuals do not translate directly into changes in distribution and abundance of fish populations.

Other relevant literature related to key species

Pörtner *et al*. (2002, 2004, 2005) have studied various aspects of oxygen transport and metabolism and have identified pejus temperature (turning worse) beyond which the ability of the animals to increase aerobic metabolism is reduced. The reduction is evident from the decline in aerobic scope which is defined as the proportional difference between resting and maximal rates of oxygen consumption. The temperature range between lower and higher pejus temperatures is much lower than that of critical temperatures beyond which the animals only survive for short periods, meaning that the temperature tolerance to changes is even lower than predicted by temperature critical values.

([51]) Group of small planktonic crustaceans found mainly in freshwater, e.g. daphnia. Marine species do occur, e.g. podon, living as zooplankton.

([52]) Region below the surface layer of the sea or lake, where the salinity gradient increases abruptly (i.e. where salinity decreases rapidly with increasing depth).

Wang and Overgaard (2007) showed that cardiac output([53]) is decreased at high temperatures and does not increase in proportion to the rise in metabolism that occurs at elevated temperatures. As a result the heart is likely to limit the aerobic scope. The population appears to decline before temperature threatens survival of the individual, thus the lower scope for growth and reproduction rather than heat induced death appears to cause the population decline. These problems are even increased by the fact that the concentration of physically dissolved oxygen in the water decreases progressively with increased temperature (Weiss 1970). Changes in temperature will affect the chemistry of aquatic systems (Arnell 1998; Harley *et al.* 2006): chemical reactions are more rapid at high temperatures and the mobility of contaminants may increase following climate change (Moore *et al.* 1997).

Key message 13

Changes in temperature affect the chemistry of aquatic ecosystems (among other, the oxygen availability) and metabolism and oxygen transport systems in fish with possible impacts on abundance and distribution of fish species.

3.3 Other related issues

Biological characteristics of relevant species of the biotic environment and of key species used in aquaculture

The most important organisms of the biotic environment of the key fish species are their prey and their predators. For the planktivorous fish species the main prey organisms are mainly small and large copepods. For the Baltic Sea, small species like *Pseudocalanus* and *Acartia* are important food items, whereas in the North Sea and the North East Atlantic additional large copepods like *Calanus finmarchicus* and *C. helgolandicus* are important.

In order to present the basic biological characteristics of the species of the biological environment of industrial key fish species, relevant information has been gathered for each species and is compiled in Annex 1-2.

Key message 14

Climate change impacts on prey and predators of industrial fish. Important organisms of the biotic environment of the industrial key fish species are their prey and their predators. For the planktivorous fish species the main prey organisms are small and large copepods([54]). For the Baltic Sea, small species like *Pseudocalanus* and *Acartia* are important food items, whereas in the North Sea and the North East Atlantic additional large copepods like *Calanus finmarchicus* and *C. helgolandicus* are important. Being important elements of the food web, their responses to climate impacts are crucial for the productivity of industrial fish stocks. Research on probable responds of relevant organisms to climate change is needed.

([53]) Cardiac output = blood flow out of the heart.
([54]) The largest class of crustaceans. Either free living or parasitic. Dominate the zooplankton but also occur with benthic species

Key species used in marine aquaculture

Table 6: Selection of key species used in aquaculture and their area of relevance in the scope of the study

Key species	Area of relevance in the study scope
Atlantic salmon	North East Atlantic
Gilthead seabream	North East Atlantic, Mediterranean
Pacific cupped oyster	North East Atlantic, Mediterranean, Black Sea
Blue mussel	North East Atlantic
European seabass	North East Atlantic, Mediterranean and Black Sea
Japanese carpet shell	North East Atlantic, Mediterranean and Black Sea
Mediterranean mussel	Mediterranean and Black Sea
Rainbow trout	North East Atlantic
Atlantic bluefin tuna	North East Atlantic, Mediterranean and Black Sea
Turbot	North East Atlantic
Grooved carpet shell	North East Atlantic, Mediterranean and Black Sea
European flat oyster	North East Atlantic
European eel	North East Atlantic, Mediterranean and Black Sea

Source: Fröse and Pauly 2007 and FAO data. "FAO Fisheries and Aquaculture Departement, Cultured Aquatic Species fact sheets".

In order to present the basic biological characteristics of key species used in marine aquaculture, relevant information has been gathered for each species and is compiled in Annex 1-3.

Exotic fish possibly entering the ecosystem

Biological invasion has become one of the most prominent elements of global change, altering biodiversity and function of natural ecosystems, causing significant economic damage. Invasions in both terrestrial and aquatic systems have shown that successful exotic species introductions may render previously stable systems unbalanced and unpredictable. However, only a limited number of exotic species are able to establish and adapt to the conditions of recipient ecosystems. The success of establishment and the consequences of invasions are difficult to predict because of the role environmental variability plays in determining the outcomes of invasion (Helmuth *et al.* 2006). Climate changes directly affect system specific attributes and therefore act as a filter to modulate the risk of and responses of invasion.

Until now, it is believed that no new marine fish species were introduced in the North-East Atlantic and adjacent seas (Nehring 2003). Nevertheless, in the freshwater systems almost 70 non-native species have been introduced, mainly intentionally, during the last century. Nehring hypotheses further, that although no new marine species have been established in Northern waters, southern species that had been found seldom in the past have increased. For the Levantine Sea (South-East Mediterranean) over 60 fish species of Indo/Pacific origin have been introduced due to the opening of the Suez Canal and some of them have already replaced native species (Goren and Galil 2005). Although this area has no direct effect on European fisheries, it shows how dramatically a species shift can alter an ecosystem.

Biodiversity in the Mediterranean has shown to be significantly changed due to anthropogenic and climatic influences. More than 300 new species (fish and others) have migrated and become established in the Mediterranean from the Red Sea via the Suez Canal. These observed changes in regard to fish and phytoplankton have had severe socio-economic consequences for the fishing industry and tourism mainly due to toxic blooms (Bethoux *et al.* 1999).

Invasive species are becoming more frequent in European coastal waters, although the dynamics of such invasions are poorly recorded and understood. Warming temperatures can facilitate the establishment and spread of deliberately or accidentally introduced species (Wonham *et al*. 2000) and could enable a wider range of species to invade and become established (MCCIP 2006).

Key message 15

Invasive species are becoming more frequent in European coastal waters. Biological invasion has become one of the most prominent elements of global change. It can alter the biodiversity and functions of natural ecosystems and can cause significant economic damage, although the dynamics of such invasions are poorly recorded and understood. Warming temperatures can facilitate the establishment and spread of deliberately or accidentally introduced species and could enable a wider range of species to invade and become established.

Effects of climate change on biological productivity and its seasonality

Synchronism between peak phytoplankton bloom abundance and fish larval stages is crucial to the survival of fish stocks (Cushing 1990) and mismatches could have severe implications for energy flow to higher trophic levels (Stenseth *et al*. 2002).

In terms of marine phenology many plankton taxa have been found to be moving forward in there seasonal cycles (Edwards and Richardson 2004). Temperate marine environments are particularly vulnerable to phenological changes caused by climatic warming, because the recruitment success of higher trophic levels is dependent on the synchronisation with the pulsed planktonic production. This also includes larval fish and indicates that climate warming has the potential to be detrimental to commercial fish via a trophic mismatch (Edwards & Richardson 2004). It also has to be mentioned that the ability and speed at which fish and planktonic communities can genetically adapt to regional climate warming is not known (Hoepffner 2006).

Modelling is a necessary tool for assessing future impacts of climate change, but it is not possible with the current state of knowledge to make quantitative predictions of changes in global marine production due to climate because of the large numbers of interactions occurring. In a comparative study with different global ocean model approaches Sarmiento *et al.* (2004) indicated that production may increase but not more than 10% over the period until 2050, but they give a low level of confidence to this estimate. In contrast observations from satellite and large scale plankton samplings have shown declines in phytoplankton and chlorophyll over the last 20-50 years which was consistent with the consequences from reduced nutrient supply relating to the strengthening of vertical density gradients (Brander. 2006). For 74% of the world's permanently stratified oceans the increase in surface warming is accompanied by a reduction in productivity, and closely coupled to climate variability (Behrenfeld *et al.* 2006).

In high latitudes the situation is the opposite. Empirical models predict an increase in primary production since large areas will become ice free as a result of higher temperatures (ACIA

2005). Increased water stability will have a positive effect on production in spite of the reduced nutrient supply, because the phytoplankton will no longer be fixed down to greater depths than their compensation depth (the depth at which respiration loss exceeds photosynthetic gain (Brander 2006). In the Arctic area climate change has enhanced the outflow of low salinity waters from the Arctic leading to a general freshening of the shelf waters which has changed the abundance and seasonal cycles of phytoplankton, zooplankton and fish populations. (Greene & Pershing 2007, Smetacek & Nicol 2005). These changes in productivity will affect biodiversity and the carrying capacity of these systems and the exploitation of marine living resources (Hoepffner *et al*. 2006).

Key message 16

Climate induced disturbance of the food web impacts on survival and productivity of industrial fish. For the survival and productivity of fish it is crucial that the abundance of fish larval stages matches together with the occurrence of the right sized zooplankton. Due to climatic changes many plankton taxa have been moving forward in there seasonal cycles. This leads to mismatches with severe implications on the survival and productivity of industrial fish stocks.

It is not possible with the current state of knowledge to make quantitative predictions of changes in global marine production due to climate change because of the large numbers of interactions occurring. However it is clear that changes in productivity and seasonality will affect the exploitation of marine living resources. Estimations indicated (with a low level of confidence) that global marine production may increase but not more than 10% over the period until 2050. In contrast observations from satellite and large scale plankton samplings have shown declines in phytoplankton and chlorophyll over the last 20-50 years. For 74% of the worlds permanently stratified oceans the increase in surface warming is accompanied by a reduction in productivity. For northern latitudes an increased production is assumed since large areas will become ice free.

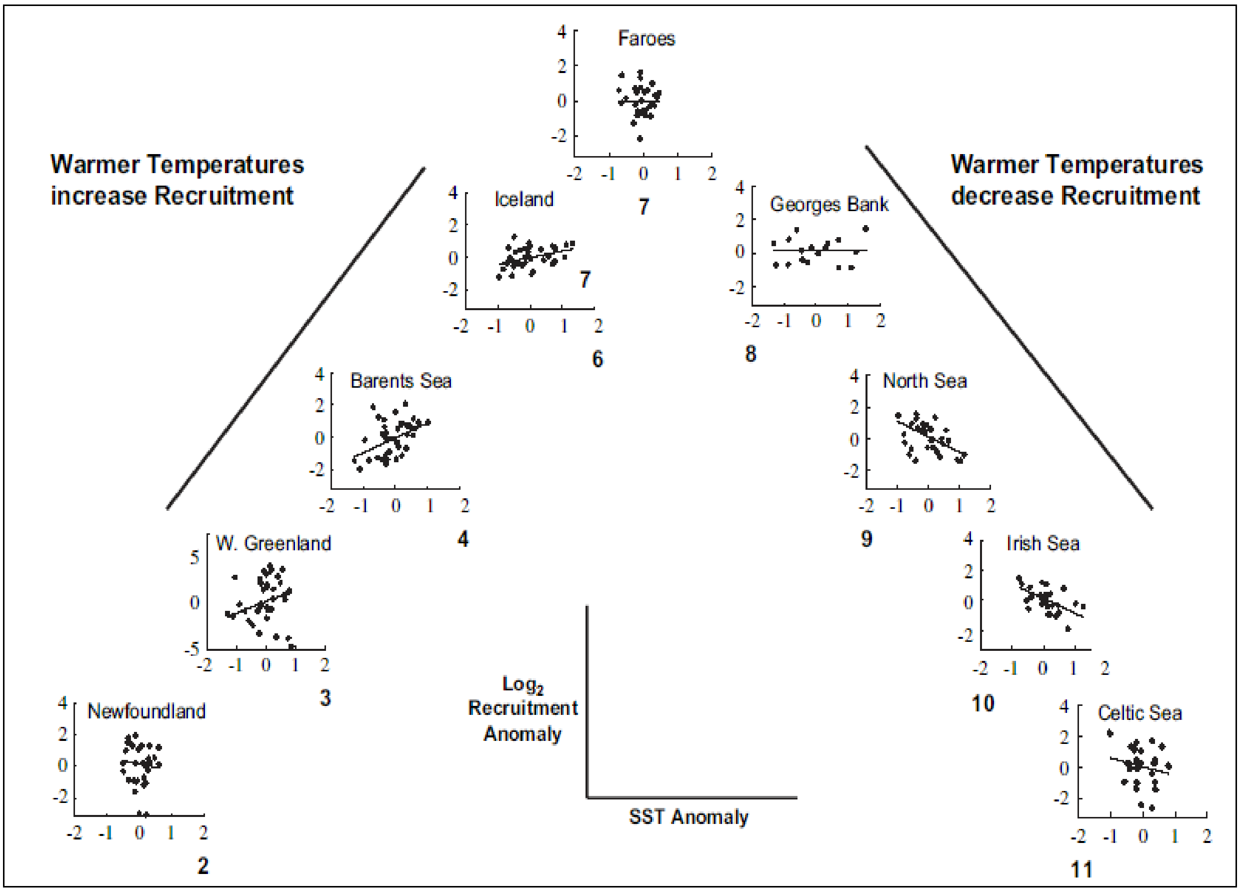
Influence of environmental conditions and fisheries on recruitment success

While many changes in the marine commercial fish stocks have been observed over the last decades in the Atlantic, it is extremely difficult to separate the effects of changes in population density and recruitment and regional climate effects from direct anthropogenic influences like fishing. Fishing has to be considered as a significant adverse anthropogenic impact (Pauly *et al*. 2005, IPCC 2007). Structural changes within the ecosystem can be controlled top down by a collapse of the population of predatory fish either by overfishing (Worm & Myers 2003, Frank *et al.* 2005) or by climatic change (Polovina 2005) and can reach down to the lower levels of the food web via trophic coupling. It has to be remembered that fishing effort is directed at catching the largest and older individuals of the population and it has recently been demonstrated that this selective fishing pressure on older and larger fish has caused rapid evolution of decreased body size and decreased fecundity (Olsen *et al.* 2004) and a loss of genetic variability (Hauser *et al*. 2002). Since older fish are able to produce offspring with a better growth and survival potential (Berkeley *et al.* 2004) these larger and older fish of long lived fish species have to be protected rather than just regulating the total numbers harvested from the population to keep the population productive, adaptive to environmental changes and fecund (Berkeley *et al.* 2004, Birkeland & Dayton, 2005).

The recruitment of cod in the North Atlantic appears to be related to sea temperatures for stocks located at the latitudinal limits for the species distribution (O'Brien *et al.* 2000). In the Northern hemisphere increasing temperatures are favourable for stocks at the highest latitudes but detrimental for those at the southern limits. Cod in the North Sea are near the southern boundary of their range and historically strong year classes have been associated with lower than average temperatures during the first half of the year (O'Brien *et al.* 2000). In addition to the increase in temperature in the North Sea the stock structure is dominated by immature young cod less than five years old.

Planque and Fredou (1999) analysed the temperature–recruitment relationship for the cod stocks in the North Atlantic and found that the relationship between sea surface temperature (SST) was generally positive for cold water stocks with adults inhabiting bottom temperatures <= 6°C. A negative relationship was found for cod from warm water cod stock experiencing bottom temperatures of >=9°C. Stocks in the midrange of bottom temperatures (7-8°C) tended to have little or no relationship between SST and recruitment (Figure 16).

Figure 16: Impact of Temperature on Fish Recruitment.



Source: Modified from Planque and Frédou (1999), from Drinkwater 2005.
Notes: The relationship between the log2 of the recruitment anomaly and sea surface temperature (SST) anomaly in °C for various cod stocks. The large axis in the bottom centre of the diagram shows the axis legends for all of the plots. The numerical value at the bottom of each plot represents the mean annual bottom temperatures for the stocks. Note that stocks are plotted with bottom temperature increasing to the right. For the cold-water stocks, the SST-recruitment relationship is generally positive while for the warm-water stocks it is negative. There is no relationship in the mid-temperature range.

Hsieh *et al.* (2006) analysed the effects of fishing and environmental variability on larval stages of exploited and unexploited species in a time series (1951-2002) in the California current system. They were able to show that exploited species showed a higher temporal variability in abundance than the unexploited species. The increased variability of the exploited species is thought to be caused by fishery-induced truncation of the age structure. Reducing the average age and length of individual fish within a population is thought to increase recruitment variability by diminishing the capacity to sustain short-term unfavourable environmental conditions. Many fish species use bet-hedging strategies to increase the survival rate of larvae under harsh and variable environmental conditions. Such hedging strategies are associated with long-tailed age structures and include age related differences in spawning locations and time and increased quantity and quality of eggs produced by older (experienced) or larger fish (Marteinsdottir & Steinarsson 1998, Berkeley *et al.* 2004). These results have immediate implications for the management of fisheries and show that beyond the potential of causing a decline in abundance, fishing can provoke greater variability in exploited populations and thereby reduced resilience and increase the risk of collapse of a fishery from environmental effects (Hsieh *et al.* 2006).

Key message 17

Many changes in the marine commercial fish stocks have been observed over the last decades in the Atlantic. It is extremely difficult to separate the effects of changes in population density and recruitment and regional climate effects from direct anthropogenic influences like fishing.

Current fishing practice decreases resilience of fish stocks against climate change impacts. Current fishing exerts pressure on older and larger fish and causes evolution of fish populations. This pressure has caused decrease in size and age structure of fish stocks, decrease in resilience against environmental effects and a loss of genetic variability and decreased adaptivity to environmental changes. As a consequence fishing can increase the risks of environmental impacts for fish stocks. **Environmentally sustainable fishing should aim to protect larger and older fish**.

Impact of future fishing activities

A major outcome of the Johannesburg Meeting 2002 was that the concept of maximum sustainable yield should be implemented for the European Union Fisheries until 2015. A way towards a better assessment of fish stocks incorporating the environment is the ecosystem approach to fisheries management (EAFM; ESA 1998, Pope & Symes 2000) as propagated in the 1992 Earth Summit in Rio. The European Union is strongly committed to the protection of the ocean and the seas. In 2005 the Commission proposed a thematic strategy for the protection and conservation of the marine environment which included a proposed Marine Strategy Directive. The aim of that directive is to ensure that all EU marine waters are environmentally healthy by 2021 so that Europeans are able to benefit from seas and oceans that are safe, clean and rich in biodiversity.

The Food and Agriculture Organisation of the United Nations (FAO) refers to future anthropogenic climate change as an example of uncertainty justifying a precautionary approach to Fisheries management (FAO, 2000, WBGU report). The report points out that global warming could have significant impacts – positive or negative – on most of the commercial fish stocks (FAO, 2002 WGBU report). The study concludes that stocks that are drastically reduced by overfishing are more vulnerable to climatic changes than sustainably exploitated stocks (FAO, 2004, Hsieh *et al.* 2006). Additionally, the response of fish stocks to environmental influences depends on population size. Healthy stocks with large production of fish larvae can better adapt to population displacement and changes in ecosystem structure (Hsieh 2006). Stocks that are greatly reduced due to over fishing respond more sensitively to environmental influences, because the probability that the minimum stock level for reproduction is not attained increases (MA 2005 b, WGBU).

A likely scenario for the North Sea is an increase in temperature, high NAO and increased inflow of Atlantic water (Stenevik and Sundby 2007). This scenario would lead to low recruitment of Atlantic cod, a northward shift of present fish species (cod, herring and sprat) and an invasion of southern species (sardine and anchovy) (Stenevik and Sundby 2007). As herring, and probably other small pelagic species, respond highly to varying hydrographic conditions, a continuous, but flexible regime seems to be adequate for future management (Miller and Munro

2004). Especially highly migrative species that alter their migration routes due to a changing environment will influence the management needs as they will probably shift from exclusively managed stocks to shared stocks (Miller and Munro 2004, Miller 2007).

Key message 18

Sustainably exploited fish stocks can better respond to climate impacts. Uncertainty on future anthropogenic climate change justifies a precautionary approach to fisheries management. Global warming could have significant impacts – positive or negative – on most of the commercial fish stocks. Stocks that are drastically reduced by overfishing are more vulnerable to climatic changes than sustainably exploited stocks. The response of fish stocks to environmental influences depends on population size. Healthy stocks can better adapt to population displacement and changes in ecosystem structure.

A flexible and adjustable fish stock management is needed. A likely scenario for the future of the North Sea is an increase in temperature, high NAO and increased inflow of Atlantic water. This scenario would lead to low recruitment of Atlantic cod, a northward shift of present fish species (cod, herring and sprat) and an invasion of southern species (sardine and anchovy). An important question is how future industrial fishing should be managed in the light of climate effects on the marine environment. As several relevant industrial key fish species (such as herring and probably other small pelagic species) respond highly to varying hydrographic conditions, future fish stock management should be continuous, but flexible and adjustable according to the responses of fish stocks to future environmental conditions. Especially highly migrative species that alter their migration routes due to a changing environment will influence the management needs.

In order to be able to adjust fisheries management in good time, research is needed that improves insight into impacts of climate change on EU fisheries and related prognoses.

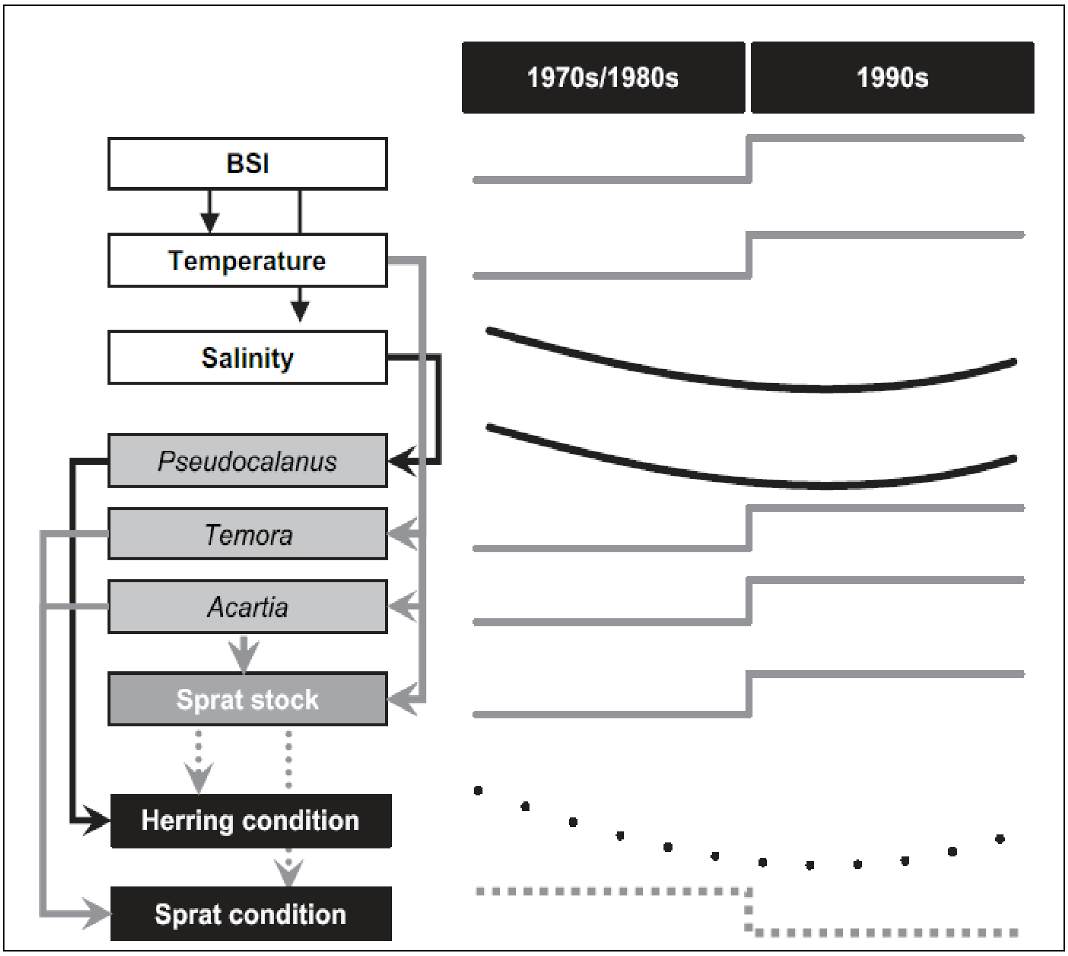
Causal chains relating climate effects – hydrography – trophic levels and fish productivity

Baltic Sea

The physical conditions in the Baltic Sea respond to climate change through direct air-sea interactions, the magnitude of freshwater run off and the interactions with the ocean at the open boundaries. These conditions are strongly linked to atmospheric forcing. High NAO indices with strong westerly winds since the late 1980s have resulted in an increase in average water temperatures and decreasing salinities (Hänninen *et al.* 2000). These changes in temperature and salinity have resulted in a change in the dominance of the main copepods from *Pseudocalanus* sp. to *Temora longicornis* and Acartia spp. (Möllmann *et al.* 2003). Similar to the copepod community the central Baltic fish community shifted from cod (*Gadus morhua*), which was dominant during the 1980s to sprat (*Sprattus sprattus*), which was dominant during the 1990s (Köster *et al.* 2003). Further the commercially important herring (*Clupea harengus*) exhibited reduction in growth. Möllmann *et al.* 2005 could show that herring condition resulted from a combined effect of changes in the feeding environment for herring and increased competition with sprat, while sprat condition appeared to be primarily determined by intraspecific([55]) competition (Figure 17).

([55]) Within one species, e.g. competition

Figure 17: Causal Relation between Climate and Fish Growth (Baltic Sea).

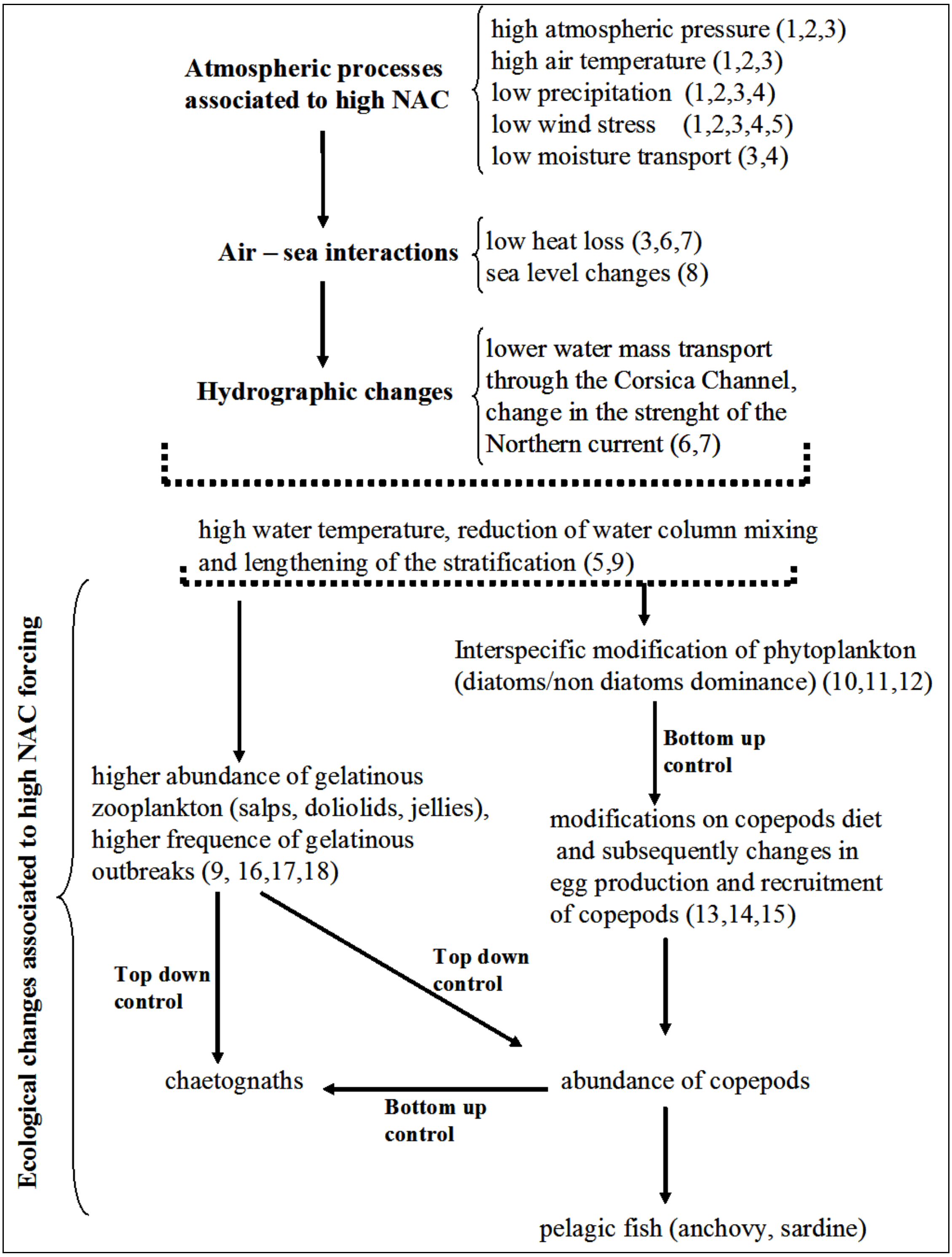


Source: Möllmann 2005.
Notes: Schematic description of relationships among climate, copepods, and pelagic fish growth: left panel: relationships among variables; right panel: resulting idealized time-trends; grey lines and arrows represent temperature-driven processes, black lines and arrows represent salinity-driven processes.

Mediterranean Sea

Molinero *et al.* (2007) have analysed the ecological effects due to climate change on pelagic copepods, chaetognaths and jellyfish in the Mediterranean. In marine ecosystems these organisms play a key role in matter and energy flow. While copepods support most food webs and the biological pump of carbon into the deep ocean, chaetognaths and jellyfish may affect the strength of the top-down control upon plankton communities. Molinero *et al.* (2007) have shown that extreme events in the long-term variability of these functional groups in the North-Western Mediterranean were tightly linked to changes of climatic forcing of the North Atlantic sector. Large-scale climate forcing has altered the pelagic food-web dynamics through changes in biological interactions, competition and predation. When the winter is warm, heat and water losses are low and reduction in the water flux transport in the Corsica Channel from the Tyrrhenian to the Ligurian Sea is expected. These hydrological regimes are linked to high values of the North Atlantic climate and effect water temperature and stratification, which alter the phytoplankton composition (diatom – non diatom dominance). Subsequently, the high temperatures and diet change (higher availability of non-diatom food) may influence egg production and recruitment in copepods and also potentially reduce food availability for chaetognaths. Moreover, the increasing water temperature, the less wind stress and precipitation, and the consequently higher stratification, favour survival and a higher reproduction in jellyfish, and hence may lead to jellyfish outbreaks. These outbreaks may impair chaetognaths and enhance mortality in the summer-autumn copepods, which then will effect the pelagic fish like anchovy and sardine feeding on copepods (Figure 18).

Figure 18: Causal Relation between Climate and Fish Growth (Mediterranean Sea).



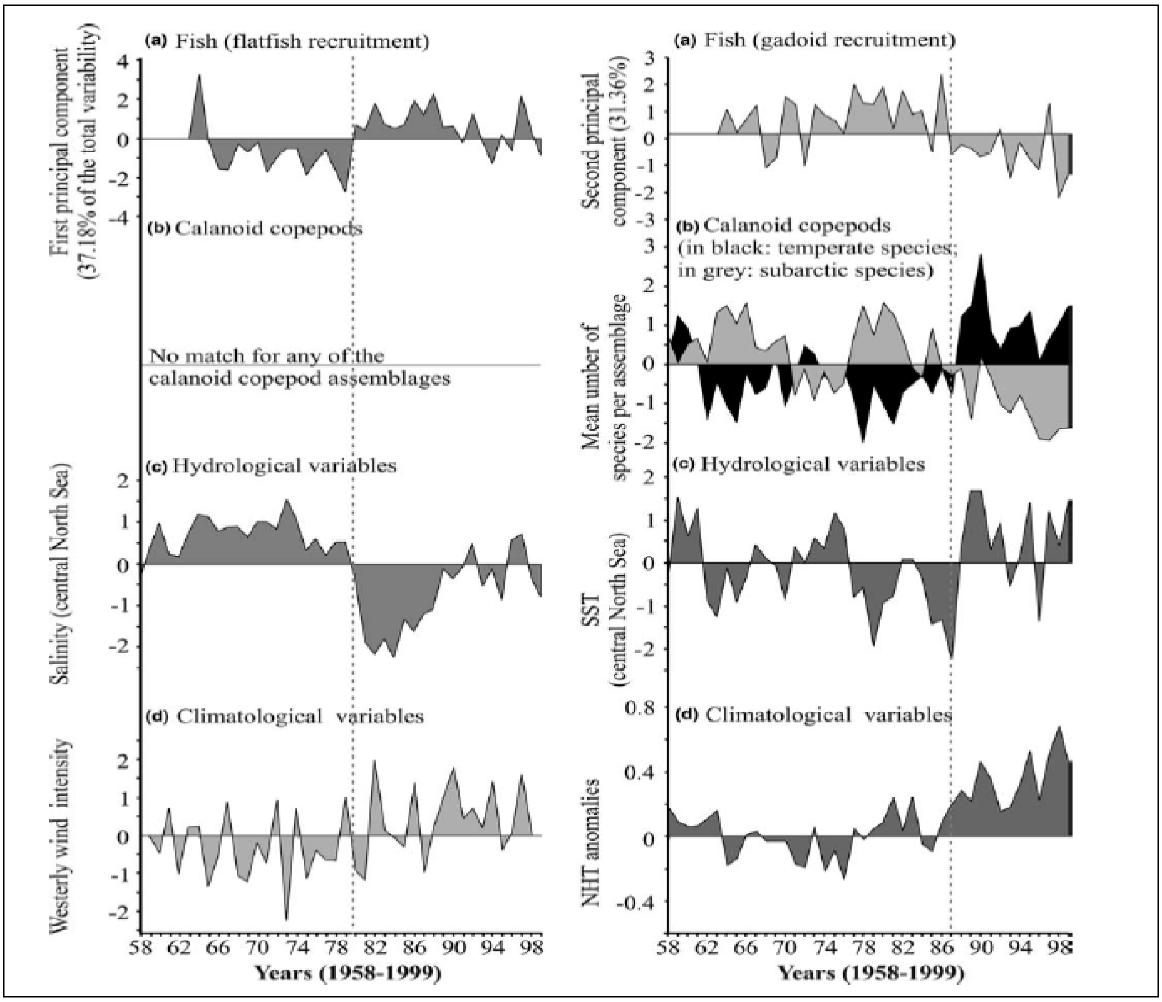
Source: Taken from Molinero et al. (2007): "Mechanisms through which the NAC (positive phase) affect Ligurian Sea hydroclimate and zooplankton long-term changes".

References: 1. Hurrell, 1995; 2. Trigo et al. 2000 ; 3. Rixen et al. 2005 ; 4. Fernandez et al. 2003; 5. Molinero et al. 2005b; 6. Astraldi 1995; 7. Vignudelli et al. 1999; 8. Tsimplis & Josey, 2001; 9.Molinero et al. 2005a; 10. Bethoux et al. 2002; 11. Goffart et al. 2002; 12. Gomez & Gorsky, 2003; 13. Ianora et al. 2003 ; 14. Carotenuto et al. (in press) ; 15. Halsband-Lenk et al. 2001; 16. Goy et al. 1989; 17. Buecher 1999. 18. Menard et al. 1994, 1997.

North Sea

Beaugrand (2004) analysed the effects causing a regime shift in the North Sea during 1982 and 1988. The evidence for changes in the ecosystem could be seen from phytoplankton to fish. Increased sea surface temperature and changes in wind intensity and direction triggered a change in the location of an oceanic biogeographical boundary along the European continental coast. Calanoid copepod species composition and diversity changed with warm water species showing an increase and cold water species decreasing in the North Sea after 1986. During a phase of high westerly wind intensity and decreased salinity an increase in flatfish recruitment was observed whereas cod recruitment was negatively influenced by an increase in sea surface temperature and an increase of temperate calanoid copepods in the North Sea (Figure 19). It is important to note, that one species will benefit while the other will decline in its abundance in relation to the same climate stressor.

Figure 19: Causal Relation between Climate and Fish Recruitment (North Sea).



Source: Beaugrand 2004.

Notes: Long-term changes in fish abundance in relation to year-to-year changes in calanoid copepod composition and hydro-meteorological forcing. (a) Long-term changes in fish recruitment (herring, cod, haddock, plaice, sole). On the left side, the first principal component (37.18% of the total variability) is mainly represented by the flatfish plaice and sole. On the right side, the second principal component (31.36% of the total variability) is mainly represented by the gadoid species haddock and cod. (b) Long-term changes in calanoid copepod species composition. No match was found between changes in calanoid and flatfish. (c) Changes in hydrological variables (salinity on the left side and sea surface temperature on the right side). (d) Changes in meteorological forcing (westerly wind intensity over the North Sea on the left side and Northern Hemisphere Temperature anomalies on the right side).

By analysing the continuous plankton recorder data (CPR) in the North-eastern Atlantic Kirby *et al.* (2006) found an increase in the abundance of pipefish (*Entelurus aequoreus*) which was related to the impact of warmer sea temperatures on reproduction and survival of this species. From 1958 to 2002 juvenile pipefish only occurred occasionally in the CPR samples. Since 2002 they appear in the samples regularly. This significant increase in larval and juvenile pipefish could be caused by an increase in average water temperature being 0.5°C higher in the period 2002-2005 compared to the average temperature during 1958-1972. One reason could be that an increase in temperature allows the males to breed more frequently, since the developmental time is reduced.

Key message 19

Studies in the North Sea, Baltic Sea and Mediterranean Sea have shown causal chains between climate – hydrography – lower and higher trophic levels – fish recruitment indicating the importance of the interactions and stressing the fact that climate change will act multi-factorially and on different levels.

Common in the observed phenomena is that climate change induces shifts in the marine ecosystem (e.g. temperature and salinity changes) that result in altered productivity of plankton prey species of relevant industrial key fish species and thus in altered productivity of the corresponding fish stocks.

Changes at the base of the food web

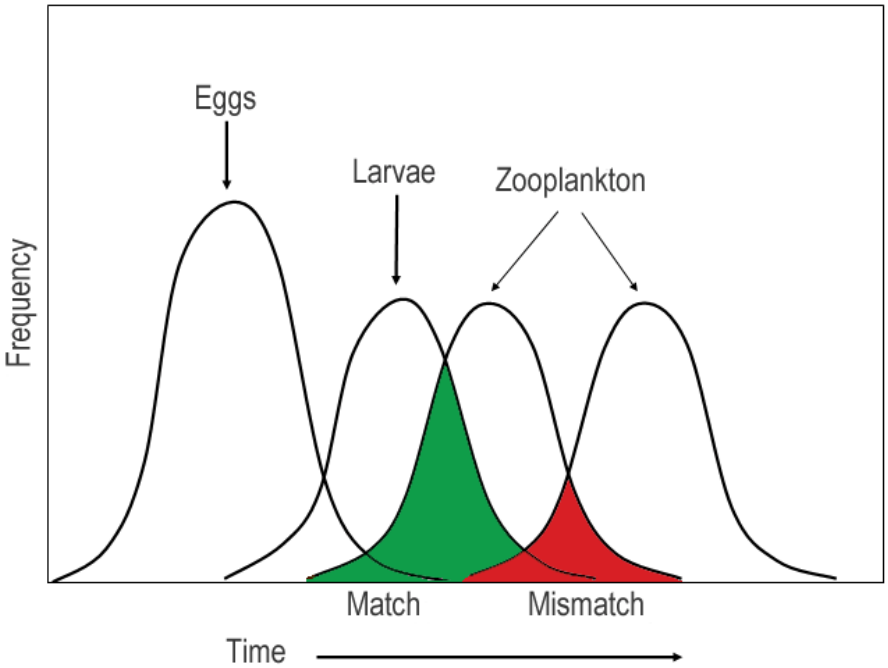
Some of the most convincing evidence for the biological response to regional climate variability comes from the bottom of the marine food web especially from phytoplankton and zooplankton communities.

Diatom blooms in spring (meaning the beginning of the pelagic seasonal cycle) have remained relatively fixed in time, since they depend on day length or light intensity rather than temperature mediated physiological responses. Organisms that are dependent on temperature to stimulate physiological developments and release of larvae have moved forward in the seasonal cycle in response to temperature (Edwards & Richardson 2004). The response to climate signals can vary between different functional groups and trophic levels. This has led to a mismatch between successive trophic levels and a change in synchrony of timing between primary, secondary([56]) and tertiary production([57]) in the North Sea (Edwards & Richardson 2004).

Changes in primary and secondary production will have an effect on fisheries production via the food web. Already in 1914 Hjort recognized that the interannual fluctuations in cod recruitment were related to the timing of the production of the food for larval fish. Cushing (1990) (Figure 20) proposed the temporal match/mismatch hypothesis referring to climate induced coupling/decoupling of these phenological relationships. It is not only the timing and the quantity that is important, the seasonal and interannual quality of the food is likely to be an important mechanistic link between climate variability and the observed changes in the recruitment success of fish (Beaugrand *et al*. 2003, Malzahn *et al*. 2007).

([56]) The rate of production of herbivorous animals by conversion of their vegetable food into animal tissue
([57]) The rate of production of carnivorous animals by conversion of their animal food into their own tissue

Figure 20: Impact of Climate on Food for Fish Larvae.



Source: Redrawn from Leggett and Deblois 1994. Schematic representation of Cushing's Match/Mismatch Hypothesis.

Atlantic cod has been overexploited in the North Sea since the late 1960s and great concern regarding the decline in biomass and recruitment exists (Cook *et al*. 1997). In addition to the effects of overfishing, fluctuations in the plankton have resulted in long term changes in cod recruitment via a bottom up control, because efficient transfer of marine pelagic production to higher trophic levels such as commercially important fish species is dependent on the temporal synchronism between production peaks. Survival of cod larvae has proved to be dependent on three key biological parameters of their prey: mean size, seasonal timing and abundance. Beaugrand *et al*. (2003) suggest a mechanism involving a match/mismatch situation by which variability in temperature affects larval cod survival. The rising temperatures in the North Sea since the mid 1980s have reduced the chances of survival of larval cod by a modification of the plankton system causing a mismatch in the size of the prey and the size of the cod. The gadoid outburst (a sudden increase in the abundance of a number of gadoid species from end of 1960s to mid 1980s) was a consequence of the highly favourable plankton situation for larval cod (Beaugrand *et al.* 2003). Edwards and Richardson (2004) suggest that marine trophodynamics have already been radically altered and will continue to do so, if temperature continues to warm. Traditional target species in the North Sea like cod are likely to continue to decline and may be replaced by species like red mullet, sardines and anchovies (Hoepffner 2006).

A negative relationship between recruitment and winter index of NAO which affects sea temperature during egg and larval stages of North Sea sandeel was shown by Arnott & Ruxton (2002). Warmer than average sea temperatures correlated with poorer than average recruitment being most pronounced near the southern limit of the species distribution. There was a positive association between recruitment and *Calanus* copepod stages abundance around the time of larval hatching suggesting that the availability of this prey species is important for young sandeel survival (Arnott & Ruxton 2002).

Around the United Kingdom, plaice and dab recruitment correlates negatively with sea temperature (Henderson 1998, Fox *et al.* 2000) Recruitment may also be affected by changes in the trophic structure of the ecosystem either with respect to feeding conditions experienced by the larvae (bottom up responses) or predation threat (top down threat).

Kirby *et al.* (2007) have shown alterations in the plankton community and its seasonality. Increase in the North Sea meroplankton([58]) mainly the larvae of a benthic([59]) echinoderm, *Echinocardium cordatum* resulted from a stepwise increase in sea temperature after 1987 with warmer conditions occurring earlier in the year. Correlation analysis showed that increase in abundance of echinoderm larvae is positively correlated with an increase in the number of days above 6°C. This dominance of larva of benthic echinoderms in the plankton in summer represents a major change in the balance between the meroplankton and the holoplankton and is indicative of a shift in resource partitioning between the benthos and the pelagial, potentially influencing larval fish.

Key message 20

Changes in primary and secondary production will have an effect on fisheries production via the food web. Climate change has already led to mismatches between successive trophic levels and thus to reduced secondary and tertiary production. If temperatures continue to rise such disturbance of the marine food web will continue and will impact on the abundance and distribution of industrial fish. This has been demonstrated in many examples:

- Diatom blooms have negative impacts on diatom-dependent organisms in the North Sea.
- A mismatch in the size of the prey and the size of the cod cause reduced survival of Atlantic cod larvae.
- Reduced abundance of the prey of young sandeel leads to reduced survival of sandeel.
- Increased sea temperature causes reduced plaice and dab recruitment around the UK.
- A shift in the balance between meroplankton and holoplankton and thus between benthos and pelagial influences the survival of larval fish.

Evidences and probable effects of climate change on aquaculture

Aquaculture development is still a matter of debate, since it can cause a great deal of environmental concern, since intensive fish culture can have a significant effect on coastal eutrophication (Naylor *et al.* 2000). Moreover, marine finfish (= A term used to separate true fish from shellfish, crayfish, jellyfish) cultivation consumes a large amount of fishmeal and is therefore dependent on the catch of wild fish (Naylor *et al.* 2000). However, the largest productions in mariculture are molluscs, which are not dependent on fish meal, could suffer from direct impact of temperature increase.

Although an increase in water temperature could be beneficial, leading to new species being cultivated in areas which were too cold in the past and a potential higher production of existing cultures, there are several threats to mariculture.

Information exists that gilthead seabream and European seabass suffer from high temperatures by stop feeding (anecdotal information from Greek net cage production sites). The mortality may increase, leading to significant loss in production. However an increase in market price can outweigh possible economic loss to a certain degree. Therefore heat waves such as the extremely hot summer 2003 have not led to great economical loss so far. Nevertheless, increasing water temperature on the production sites may lead to production failures and

([58]) Meroplankton is composed of organisms that are planktonic for only a part of their life cycles, usually the larval stage. Examples of meroplankton include the larvae of sea urchins, starfish, crustaceans, marine worms, and most fish.
([59]) Refers to animals and fish that live on or in the water bottom.

significant economic impacts. A possible strategy to avoid such economic losses may be to shift the production sites from shallow water close to the coast to deeper and cooler water. Another strategy may also be to cultivate other species.

Possible effects of climate change would be that rising temperatures could increase growth rates and feed conversion efficiency for some species (Lehtonen 1996), but may cause thermal stress for cold water species and intertidal organisms like shellfish. Moreover temperature change could affect diseases of farmed species and could also increase the disease susceptibility. The increased occurrence of harmful algae and jelly fish blooms could lead to fish kills and the closure of shellfish harvesting areas (Kent & Poppe 1998). Storm damages to fish farms and net pen cultures may increase escapes and could result in fewer suitable areas being available decreasing the development of aquaculture (MCCIP 2006).

For the production of Atlantic salmon along the Norwegian coast, a move of the production centres northwards is assumed when temperature will increase (Stenevik & Sundby 2006).

Key message 21

Positive and negative effects are expected for marine aquaculture. Productivity may rise due to increasing growth rates and feed conversion efficiency for some species used in aquaculture. It could also be possible to introduce new species to aquaculture. On the other hand negative effects such as thermal stress for coldwater species and intertidal organisms, diseases and disease susceptibility are expected. Also damages to fish farms due to extreme weather events are possible. It may be necessary to shift production centres to more appropriate locations according to changed environmental conditions. In addition there are concerns that heat waves may cause significant economic impacts in particular to production sites that are situated in shallow water close to the coast. It is unknown as to whether the positive effects will outweigh the negative effects or vice versa.

4. Documentation and critical assessment of results

A thorough and comprehensive literature review of relevant and up to date scientific literature and relevant studies has been carried out during January to May 2007 by experienced experts of the project team. The documentation of the results of literature research enables to identify each relevant reference related to each specific subject of interest (climate change effects on "properties of water", "key fish species" and "other related issues") and subchapters (See Table 7). The chapter "Bibliographies" contains an alphabetic list of literature references.

On the basis of the findings from the literature review a number of 40 climate change driven phenomena related to specific trends and effects have been identified. The phenomena are listed in Table 2. They are allocated to the issues "properties of seawater", "biology of key species", "biological environment", "productivity" and "fisheries". It has to be kept in mind that a clear allocation to the issues is not always possible. For example effects related to the biology of industrial key species are usually also related to productivity of the fishing industry. For each phenomenon a degree of confidence has been attributed on the basis of the reliability of the literature sources and the frequency of similar findings.

A critical assessment of the results from the literature review can be summarised as follows:

Man-made greenhouse gases continue to rise and contribute a large proportion to climate change and changes of the marine ecosystem. Greenhouse gases are a threat for the already weakened fish stocks and their releases should be minimised.

It has been demonstrated, that climate change impacts on the European marine ecosystems. Direct impacts are particularly related to changes of temperature, sea level rise, acidification and salinity. Expected impacts will have negative and positive effects on marine productivity and European industrial fisheries. Generally, it is expected, that climate change impacts may be more severe in semi-enclosed seas than in the open seas.

In addition to temperature and salinity, food availability and suitable spawning grounds determine the large scale distribution of fish. Direct and indirect climate effects can lead to a shift of fish populations, the invasion of alien species and even to the disappearance of species. Significant effects have been observed on industrial key fish species and their biological environment. Changes in primary and secondary production will have an effect on fisheries production via the food web. Climate change has already led to mismatches between successive trophic levels and thus to reduced secondary and tertiary production. Disturbation of marine trophodynamics will continue if temperatures will continue to rise.

At the present state of knowledge it is not possible to assess the economic impacts from climate change on European fisheries industry and on aquaculture. According to existing climate change scenarios, a number of expected impacts on industrial fish species indicate an increase of marine productivity and industrial fish populations whereas other impacts appear to contribute to a corresponding decrease. It is unknown, whether the positive effects will outweigh the negative effects or vice versa.

An important question is how future industrial fishing should be managed in the light of climate effects on the marine environment. In order to be able to adjust fisheries management in good time, research is needed that improves insight into impacts of climate change on EU fisheries and related prognoses.

For several aspects research needs have been identified:

Research needs related to effects on properties of water and key fish species:

- Available global circulation models driven by climate scenarios have been treating the marine environment and changes in ocean climate in a simplified way. Methodologies have to be further developed for the downscaling of global models to regional scale models. In this context further studies on the behaviour of the thermohaline circulation to a changing climate are needed.
- Lethal criteria are usually useless for assessing direct impacts on fish. If at all, controlling and directive criteria may be used. Research is needed in this aspect.
- Distributional shifts have been shown in many cases, but since the considered species are often heavily exploited, the establishment of direct causal relationships – which would be a prerequisite for reliable prognosis – between temperature and distribution patterns is difficult. Reliable prognosis on the probable development of fish stocks due to climate change effects are only possible for some intensively investigated species (e.g. Atlantic cod). Separation from other impact factors is difficult. Research is needed for the assessment of climatic effects in the presence of non-climatic stressors.
- Even if several examples for temperature or salinity induced interactions (food organisms, predators, competitors, reproduction) resulting in the shift of populations have been observed and can be used to explain some interactions and internal changes in ecosystems, there is a need to conduct studies on population and community levels, since direct climatic effects on individuals do not translate directly into changes in distribution and abundance.
- Special emphasis should be on the research of semi-enclosed areas, since they will be most affected by climate driven changes and therefore highly susceptible.

Research needs related to effects on the biological environment of industrial fish species:

- Being important elements of the food web, the responses of species of the biological environment of fish to climate impacts will be crucial for the productivity of industrial fish stocks. Research on probable responds of relevant organisms to climate change is needed.
- Invasive species are becoming more frequent in European coastal waters, but the dynamics of such invasions are poorly recorded and understood. Research on the effects of invasion in the context of community and ecosystem interactions is needed.
- It is not possible with the current state of knowledge to make quantitative predictions of changes in global marine production due to climate because of the large numbers of interactions occurring.
- Long-term data gathering and time series analysis is necessary to study the effect of climate change on the marine environment. Besides monitoring, these long-term surveys should include process studies to gain a better understanding of the underlying concepts that determine the reaction patterns of the key species within the system. The access and recovery of marine data for time series analysis should be given a high priority.
- Research on the impacts of ocean acidification on marine biota and their physiology, especially on biological productivity and the offspring of fish, as they are most vulnerable, is needed. Process studies, experimental work and field studies should be integrated into biogeochemical, circulation and climate models for the evaluation of the future impacts of ocean acidification.

Research needs related to fishing impacts:

- Information on the evolution of fish in the marine environment, the change in genetic diversity and adaptation pattern is scarce. Development and application of adaptive measures to climate change are needed.
- Monitoring and evaluation of suitable areas for spatial closure (Marine Protected Areas (MPAs)) is needed.
- Recovery strategies for heavily exploited species have to be determined and evaluated; within this field further research is needed.
- Research is needed on sustainable exploitation and appropriate fish stock management that maximises the adaptivity of fish stocks to environmental changes.
- The ecosystem approach to fisheries management requires insight into the infrastructure of fish stocks and their function. Therefore detailed information about the ecology of important marine species, their life cycles, migration patterns, their biological background and their interaction with the biotic and abiotic environment([60]) is needed. Further development of advanced ecosystem models and multidisciplinary research is necessary to improve the detection, prediction and forecasting methods for the response of the ecosystem to climate change and to allow an effective management and the sustainable use of resources.

([60]) The non-living environment, comprised by all abiotic factors, e.g. temperature, salinity.

5. Conclusions and recommendations

- **Greenhouse gases contribute to climate change and are a threat for industrial fishing**

Man-made greenhouse gases continue to rise and contribute in a large proportion to climate change and changes of the marine ecosystem. Greenhouse gases are a threat for the already weakened fish stocks and their releases should be minimised.

- **Properties of water are already changing**

It is scientific consensus that climate change is reality. ***Temperatures will increase and sea level will rise.*** Warming of the climate system has been detected in changes of surface and atmospheric temperatures, temperatures in the upper several hundred metres of the ocean and in contributions to sea level rise. Average global temperatures have increased by ~0.6°C and sea level has risen 0.17m over the past century. During this period, both marine and freshwater systems have warmed. The coastal marine climate of Europe is predicted to continue to warm throughout the 21^{st} century, with the forecast for the sea surface temperature to increase by 0.2°C per decade. ***Model estimates predict ocean acidification***. The pH reduction in the ocean surface range from 0.3 to 0.5 units over the next 100 years and from 0.3 to 1.4 units over the next 300 years. ***Salinity will change.*** In the nordic seas and the Baltic decreases in salinity are expected whereas in the Mediterranean salinity is expected to increase.

The Atlantic thermohaline circulation will be weakened. The water bodies of the North Sea and Arctic regions interact by exchange of cold and warm water flows are driven by the Atlantic thermohaline circulation. The flow intensity is influenced by climate change. Currently the flow intensity may already be reduced by 30%. It is unlikely that the circulation will shut down completely which would have strong impacts on current patterns (e.g. a short term sea level rise in the North Sea of 1m, a long term global sea level rise of 0.5m, a southward shift of the tropical precipitation belt and a reduction of biomass in the Atlantic by 50%).

Stratification will increase. It has been demonstrated, that climate change causes increased stratification of the Baltic Sea, the North Sea and the Mediterranean Sea. Stratification of the water column leads to natural barriers where organisms can concentrate or where organisms have to pass through. Stratification increases with increasing salinity and temperature. Increased stratification hinders mixing with deep water and causes reduced replenishment of nutrients.

Changed circulation and stratification will change the geographical distribution of organisms. Currents play an important role in transporting organisms like plankton and fish over large distances and can thus increase their distribution range. On the other hand, currents also act as a biogeographical barrier between the water masses on both sides of a current. They reduce the exchange of organisms across the current. Warming may lead to weakening of alongshore currents, thus decreasing the distribution with the alongshore current, but breaking down the barrier between coastal and offshore water. This may lead to range extension of organisms previously trapped near the coast. All these effects impact (positively or negatively) on primary production.

Climate change impacts may be even more severe in semi-enclosed seas than in the open seas. Expected impacts will have negative and positive effects on marine productivity. According to climate change scenarios for the Baltic Sea the prognosis for a decrease of salinity ranges from 8% to 50% and for the increase of the sea surface water from 2 to 4°C. In the North Sea region, the prognosis for salinity is variable with expected increases and decreases in different areas of the North Sea. The sea surface temperatures are predicted to rise about 1.6°C to 3.0°C in the northern North Sea and 3.0°C to 3.9°C in the shallower southern North Sea. According to climate change scenarios salinity and temperatures will increase in the Mediterranean Sea.

- **The North Atlantic Oscillation**

The North Atlantic Oscillation impacts on the European marine ecosystem. Many aspects of the winter climate in the European area are strongly influenced by the so called "North Atlantic Oscillation" (NAO) which dominates the atmospheric behaviour in the North Atlantic. Several indices for the NAO have been defined. The NAO affects all marine trophic levels. Recruitment of industrial fish is linked to the NAO index as demonstrated for the gadoid outburst (concerning cod, haddock, whiting and saithe) in the North Sea and for herring and sardine recruitment in the Northeast Atlantic. The NAO is highly unpredictable, although it is possible to reconstruct the NAO from sea surface temperature.

The ex post analyses of the NAO index and the relation to observed impacts on the marine ecosystem may enable to develop models for the prognosis of future impacts.

- **Effects on industrial key fish species have been observed in many cases**

Changes in temperature can lead to shifts of fish populations, the invasion of alien species and disappearance of species. Temperature is a fundamental component of the niche of fish. Fish tend to select thermal habitats that maximise their growth rate. However, predicting the effects of temperature change on fish is difficult. In addition to temperature, food availability and suitable spawning grounds determine the large scale distribution of fish. Direct and indirect climate effects can lead to a shift of fish populations, the invasion of alien species and even to the disappearance of species. In several studies the abundance and distribution of fish and zooplankton related to a rise in sea temperature was observed.

Warm fish species invade "cold" ecosystems. Several warm fish species have invaded "cold" ecosystems and cold species which used to be relatively abundant in "warm" ecosystems have become very scarce or have disappeared. E.g. sprat and mackerel have become very scarce or disappeared from the Mediterranean Sea. Shifts have been shown in many more cases. However, since the considered species are often heavily exploited, the establishment of direct causal relationships between temperature and distribution pattern is difficult. Reliable prognoses on the probable development of fish stocks due to climate change effects are only possible for some intensively investigated species (e.g. Atlantic cod). Separation from other impact factors is difficult. Research is needed.

Climate change influences abundance and distribution of industrial fish. Changing climate has a direct influence on survivorship, dispersal, fertility and behaviour of individuals and thus on abundance and distribution. Prognoses are difficult since many factors other than climate impacts play an important part in determining species distribution and the dynamics of these changes. Changes in the geographical range extension have contributed to an increased productivity of cod and haddock around Greenland. This has been a response to dramatic warming in 1920 to 1930. The primary cause for these changes were bottom up processes due to increased phyto- and zooplankton production.

Mean bottom temperatures can be crucial for the growth rate of a fish stock. According to simplistic simulations developed for the North Sea cod increasing bottom temperatures are expected to have a negative impact on the growth rate of cod. Such approaches demonstrate that the inclusion of environmental factors in fish population models can alter the prognosis on how populations will behave. Simulations can provide management advice and show that the inclusion of environmental effects may become increasingly important in fish stock management.

As demonstrated by several examples, ***climate change can have an indirect positive or negative effect on reproduction success of industrial fish.*** In the case of the Norwegian spring spawning herring a climatically driven increase in water temperature has the effect that fish populations do not participate in the usual spawning process. This has an indirect effect on the reproductive potential and directly impacts on commercial fisheries (loss of stocks). Blue fin tuna could also reproduce outside of its traditional spawning grounds during warm periods. This would have a positive effect on the productivity of the blue fin tuna stock.

Climate change causes shifts of industrial fish populations. Several examples for temperature or salinity induced changes of interactions (food organisms, predators, competitors, reproduction) result in the shift of populations. These examples can be used to explain some interactions and internal changes in ecosystems. However there is a need to conduct studies on population and community levels, since direct climatic effects on individuals do not translate directly into changes in distribution and abundance of fish populations.

Effects of climate change on plankton lead to the shift of fish populations. Many industrial fish species are directly plankton dependent. Plankton-feeding fish species, in particular sardine and anchovies, show strong natural fluctuations with climate variations. Investigations related to climatic warming indicated shifts from a dominance of northern species to a dominance of southern species. Shifts in boundaries using more than 60 different North Sea fish species showed a shift of boundaries of half of the species (exploited and non-exploited) with a northward trend. Some species may have reached their tolerance limits, such as cod in the North Sea, resulting in northwards movement of their populations. The decrease in cod was correlated with changed species assemblages, stock decline and smaller average body size of the zooplankton. This can probably be attributed to climate change. The shift of populations (e.g. as demonstrated for the Atlantic cod) can lead to the complete loss of stocks at the regional level.

- **Effects on the biological environment impact on industrial fish species**

Climate change impacts on prey and predators of industrial fish. Important organisms of the biotic environment of the industrial key fish species are their prey and their predators. For the planktivorous fish species the main prey organisms are small and large copepods. For the Baltic Sea, small species like *Pseudocalanus* and *Acartia* are important food items, whereas in the North Sea and the North East Atlantic additional large copepods like *Calanus finmarchicus* and *C. helgolandicus* are important. Being important elements of the food web, their responses to climate impacts are crucial for the productivity of industrial fish stocks.

Invasive species are becoming more frequent in European coastal waters. Biological invasion has become one of the most prominent elements of global change. It can alter the biodiversity and functions of natural ecosystems and can cause significant economic damage.

Climate induced disturbance of the food web impacts on survival and productivity of industrial fish. For the survival and productivity of fish it is crucial that the abundance of fish larval stages matches together with the occurrence of the right sized zooplankton. Due to climatic changes many plankton taxa have been moving forward in there seasonal cycles. This leads to mismatches with severe implications on the survival and productivity of industrial fish stocks. If temperatures continue to rise such disturbance of the marine food web will continue and will impact on the abundance and distribution of industrial fish.

This has been demonstrated in many examples: Diatom blooms have negative impacts on diatom-dependent organisms in the North Sea. A mismatch in the size of the prey and the size of the cod cause reduced survival of Atlantic cod larvae. Reduced abundance of the prey of young sandeel leads to reduced survival of sandeel. Increased sea temperature causes reduced plaice and dab recruitment around the UK. A shift in the balance between meroplankton and holoplankton and thus between benthos and pelagial influences the survival of larval fish.

- **Economic implications for industrial fishery**

Climate change can have severe economic implications on industrial fishery. Assuming that industrial fishery is directly linked to marine production, an increase or decrease in productivity of 10% would result in an economic gain or loss of more than €200 million. It is difficult to assess the impacts of shifts of fish stocks on industrial fishing because the shift related decrease is usually accompanied by a corresponding increase of another species.

Positive and negative economic impacts on industrial fishery are expected. It is not possible with the current state of knowledge to make quantitative predictions of changes in global marine production due to climate change because of the large numbers of interactions occurring. However it is clear that changes in productivity and seasonality will affect the exploitation of marine living resources. Estimations indicated (with a low level of confidence) that global marine production may increase but not more than 10% over the period until 2050. In contrast observations from satellite and large scale plankton samplings have shown declines in phytoplankton and chlorophyll over the last 20-50 years. For 74% of the worlds permanently stratified oceans the increase in surface warming is accompanied by a reduction in productivity. For northern latitudes an increased production is assumed since large areas will become ice free.

- **Possible impacts on aquaculture**

Climate change can have severe economic implications on marine aquaculture. Bearing in mind that marine aquaculture in the EU is related to a market value around €2 billion there are concerns that climate change will lead to significant economic impacts due to climate change.

Positive and negative effects are expected. Productivity may rise due to increasing growth rates and feed conversion efficiency for some species used in aquaculture. It could also be possible to introduce new species to aquaculture. On the other hand negative effects such as thermal stress for coldwater species and intertidal organisms, diseases and disease susceptibility are expected. Also damages to fish farms due to extreme weather events are possible. It may be necessary to shift production centres to more appropriate locations according to changed environmental conditions. In addition there are concerns that heat waves may cause significant economic impacts in particular to production sites that are situated in shallow water close to the coast. It is unknown as to whether the positive effects will outweigh the negative effects or vice versa.

- **The impacts of industrial fishing on key species**

Many changes in the marine commercial fish stocks have been observed over the last decades in the Atlantic. It is extremely difficult to separate the effects of changes in population density and recruitment and regional climate effects from direct anthropogenic influences like fishing.

Current fishing practice decreases resilience of fish stocks against climate change impacts. Current fishing exerts pressure on older and larger fish and causes evolution of fish populations. This pressure has caused decrease in size and age structure of fish stocks, decrease in resilience against environmental effects and a loss of genetic variability and decreased adaptivity to environmental changes. As a consequence fishing can increase the risks of environmental impacts for fish stocks. ***Environmentally sustainable fishing should aim to protect larger and older fish***.

Sustainably exploited fish stocks can better respond to climate impacts. Uncertainty on future anthropogenic climate change justifies a precautionary approach to fisheries management. Global warming could have significant impacts – positive or negative – on most of the commercial fish stocks. Stocks that are drastically reduced by overfishing are more vulnerable to climatic changes than sustainably exploited stocks. The response of fish stocks to environmental influences depends on population size. Healthy stocks can better adapt to population displacement and changes in ecosystem structure.

A flexible and adjustable fish stock management is needed. A likely scenario for the future of the North Sea is an increase in temperature, high NAO and increased inflow of Atlantic water. This scenario would lead to low recruitment of Atlantic cod, a northward shift of present fish species (cod, herring and sprat) and an invasion of southern species (sardine and anchovy). An important question is how future industrial fishing should be managed in the light of climate effects on the marine environment. As several relevant industrial key fish species (such as herring and probably other small pelagic species) respond highly to varying hydrographic conditions, future fish stock management should be continuous, but flexible and adjustable according to the responses of fish stocks to future environmental conditions. Especially highly migrative species that alter their migration routes due to a changing environment will influence the management needs.

In order to be able to adjust fisheries management in good time, research is needed that improves insight into impacts of climate change on EU fisheries and related prognoses.

- **Policy Options**

Man-made greenhouse gases continue to rise and contribute to a large proportion to climate change. Climate change impacts in many ways directly and indirectly on European industrial fisheries and marine aquaculture. In total a market volume of more than €4 billion is at stake.

There is no doubt that climate change will impact positively and negatively on the marine ecosystem and on the EU fisheries and marine aquaculture. It is uncertain whether the positive or negative impacts of climate change on the EU fisheries will preponderate. In many aspects the knowledge and understanding of relations and interactions between the marine ecosystem, industrial fishing, marine aquaculture and climate change is deficient.

Considering possible policy choices, ***7 general options have been identified*** (they are discussed below):

Option 1. ***No action option***.
Option 2. ***Decrease of greenhouse gases***. Taking legislative and policy measures and supporting existing initiatives to decrease releases of greenhouse gases.
Option 3. ***Strategies to increase resilience of fish populations***. Developing strategies and concepts that enable a sustainable exploitation of fish stocks in a way that fish stocks have a higher resilience to environmental impacts.
Option 4. ***Strategies to improve fish stock management***. Developing flexible fish stock management strategies and concepts that are adjustable to the responses of fish stocks to environmental conditions.

Option 5. ***Strategies to improve aquaculture***. Developing strategies and concepts in order to minimise negative impacts on marine aquaculture.
Option 6. ***Stimulating research***. *S*timulation of relevant research and sharing of knowledge.
Option 7. ***Compensate negative impacts***. Provision of support (financial or other) in order to compensate negative impacts of climate change.

Discussion of the options:

Option 1) As it is not proven that climate change will have an overall negative impact on EU fisheries a possible option could be to take no action at all. The "no action option" has the advantage that it is not related to any initial costs. Positive impacts of climate change on fisheries such as increased production of the marine ecosystem due to increased temperatures will not be foreclosed. On the other hand it appears to be unacceptable not to act at least against negative climate change impacts (including cost implications) as these will fully occur without any counteraction. Option 1 is not recommended.

Option 2) This option is related to the support of a European policy to combat climate change (e.g. the EU greenhouse gas monitoring and reporting or the emission trading schemes) and appropriate measures that aim to minimise atmospheric concentrations of greenhouse gases. As greenhouse gas emissions cause climate change, this option will contribute to tackling climate change at its source. Option 2 is recommended.

Option 3) It has been demonstrated that historic and current industrial fishing decreases resilience of fish stocks against environmental changes. Option 3 aims to develop strategies for sustainable fishing in the sense that fish stocks have a higher resilience to environmental changes. This could e.g. be possible by exploring options on how to reduce the catches of older and larger fish or by the establishment of marine protected areas. This option aims to adapt current fish exploitation to respond to impacts of climate change. This is in line with the objectives of the EU Adaptation Programme under the European Climate Change Programme (ECCP) to explore options to improve Europe's resilience to climate change impacts in different sectors. The Common Fisheries Policy (CFP) has a key role in managing fish populations and should take possible climate impacts on fish stocks into account. It could be an appropriate instrument to implement corresponding strategies to increase the resilience of fish stocks against impacts from climate change. Option 3 is recommended.

Option 4) Fish stocks will respond to climate change by specific behaviour e.g. with time or spatial shifts of fish stock abundance or changes in migration routes. Option 4 aims to react in fish stock management to the responses of fish stocks in order to allow an efficient exploitation. This will require a flexible regime of fish stock management in order to avoid negative economic impacts. This option aims to adapt current fish stock management to impacts of climate change and is therefore in line with the objectives of the EU Adaptation Programme under the ECCP. It is vital to take into account the sustainability aspects in the sense of option 2. Otherwise there is a risk, that the improved fish stock management will be used to maximise the exploitation of marine resources without taking account of the need to increase the resilience of fish stocks against environmental impacts. As for option 3, the CFP could be instrumental in implementing corresponding strategies. Option 4 is recommended.

Option 5) Similar to options 3 and 4, this option is an adaptation strategy in line with the EU adaptation programme under the ECCP. It aims to avoid negative impacts on marine aquaculture. Possible elements of the strategy may e.g. be to move production centres northwards, to move production sites to deeper and cooler water or to focus on new species.

Similar to options 3 and 4, the CFP could be instrumental in implementing corresponding strategies. Option 5 is recommended.

Option 6) In particular options 3 to 5 are related to significant research needs. It is indispensable to have appropriate knowledge and insight in relations and interactions between the marine ecosystem, industrial fishing, marine aquaculture and climate change. A sound knowledge base is a prerequisite for the development of efficient strategies for sustainable fishing, fish stock management and for marine aquaculture in view of the threats of climate change. Specific research needs are listed in chapter 4. The EU could stimulate and/or support corresponding research in order to improve the factual basis for its policy decisions and the strategies to be developed and could contribute to the dissemination of the created knowledge. Option 6 is recommended.

Option 7) This option concerns the provision of support (financial or other) in order to compensate negative impacts of climate change such as compensation payments for regions where significant economic impacts have occurred as an impact of climate change (e.g. due to outfalls of aquaculture production after heat waves or due to breakdown of fish recruitment in a region if a fish population has regionally disappeared). Such payments could provide short term help to the region concerned. However, compensation measures are reactive and not directed to the future. Proactive and knowledge-based approaches seem to be preferable (e.g. altered aquaculture production strategies or fish exploitation management. Option 7 is not recommended.

The table "Overview of policy options and their pros and cons" in the executive summary gives a fast overview of the identified policy options and their pros and cons.

ANNEXES

Annex 1. Biological characteristics of species

Annex 1-1: Biological characteristics of industrial key fish species

Atlantic herring (*Clupea harengus* L. 1758) North East Atlantic, North Sea, Baltic Sea

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
45cm	25 years	Pelagic, marine and brackish; 0-200m	1°C – 18°C

Minimum population doubling time: 1.4 – 4.4 years (medium)

The herring was and is one of the most important commercially used species in the North Atlantic. It forms schools and shows complex feeding and spawning migrations. Herring perform daily vertical migrations, staying in deep water during the day and ascending during the night to follow the vertical movement of the prey. They feed on planktonic organisms like copepods and pelagic snails. The adult fish are a main prey item for predatory fish like mackerel and cod. Herring is a benthic spawner and lays eggs on substrate near the coast. The survival of eggs and larvae is dependent on predation and abiotic environmental conditions. In Europe several distinct stocks have been identified, differing in migration routes and spawning times.

Sprat (*Sprattus sprattus* L. 1758) North East Atlantic, North Sea, Baltic Sea, Mediterranean Sea

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
16cm	6 years	pelagic, marine and brackish; 10-150m	temperate

Minimum population doubling time: less then 15 month (high)

Sprat form schools like herring and also perform migration between their feeding and spawning grounds. They stay in deep water during the day and follow their prey to the surface at night. Main prey is small crustacean plankton. Sprat is a pelagic spawner and can produce up to fourteen thousand eggs throughout the spawning season (Muus and Nielsen 1999). The adults are main prey for piscivorous fish (i.e. cod, mackerel).

European pilchard (*Sardina pilchardus* Walbaum 1792) North East Atlantic, Mediterranean

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
25cm	15 years	pelagic, marine and brackish; 10-100m	subtropical

Minimum population doubling time: 1.4 – 4.4 years (medium)

European pilchard form schools and show vertical migrations from 100m at day to 20m at night following their planktonic prey. They can produce up to fifty thousand pelagic eggs (Muus and Nielsen 1999).

European anchovy (*Engraulis encrasicolus* L. 1758) North East Atlantic, Mediterranean

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
20cm	3 years	pelagic, marine, brackish and freshwater; 0-400m	subtropical

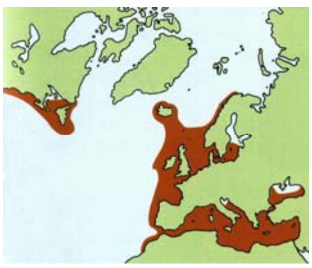
Minimum population doubling time: less than 15 months (high)

European anchovy is mainly a coastal species, regularly entering the estuaries and even lakes during spring (spawning time). They migrate further north in the summer months and spawn from April to November pelagic eggs in the upper 50m. During winter they stay in deep water (down to 150m) (Whitehead *et al.* 1988). Anchovy are planktivorous fish, preying both on zooplankton and phytoplankton (James 1988)

Atlantic mackerel (*Scomber scombrus L. 1758)* North East Atlantic, Mediterranean

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
60cm	17 years	pelagic, marine and brackish; 0-1000m	temperate

Minimum population doubling time: 1.4 – 4.4 years (medium)

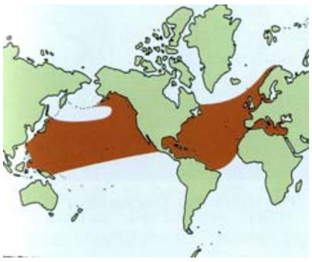


Mackerel are abundant in cold water and temperate shelf areas. In the North-East Atlantic two stocks could be distinguished, the North Sea stock (east) and the British Isles stock (west). The fish form large schools near the surface. They overwinter in deep water, moving closer to the shore in spring when water temperature rises. Eggs and larvae are pelagic. The adults feed on zooplankton and small fish.

Northern bluefin tuna (*Thunnus thynnus* L. 1758) Atlantic, Mediterranean

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
460cm	15 years	pelagic, marine and brackish; 0-200m	3°C – 29°C

Minimum population doubling time: 4.5 – 14 years (low)



Northern bluefin tuna is a very large piscivorous fish. They migrate over very long distances, following their prey, mostly schooling fish. Staying oceanic most of the year, they move near the coast in the Mediterranean during spawning time in the summer (June). Females can produce up to ten million eggs per spawning season. The eggs are laid in the open water. Natural predators are mainly different shark species, Orcas and some birds.

Blue whiting (*Micromesistius poutassou* Risso 1827) North Sea

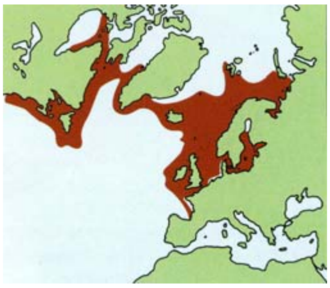
Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
50cm	20 years	pelagic, marine	temperate

Minimum population doubling time: 1.4 – 4.4 years (medium)

Blue whiting are distributed over the continental slope and shelf to more than 1000m, but stay mainly at 300-400m. They stay near the bottom during the day and move to surface water during the night. Main prey is crustacean plankton for the juveniles and small fish and cephalopods([61]) for the adults. Spawning time is in spring off the coast of Great Britain, Iceland and Norway. The eggs are pelagic.

Atlantic cod (*Gadus morhua* L. 1758) North East Atlantic, North Sea, Baltic Sea

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
200cm	25 years	benthopelagic, marine and brackish; 0-600m	-1°C – 10°C



Minimum population doubling time: 1.4 – 4.4 years (medium)

Atlantic cod is a widely distributed species. It lives and feeds near the bottom (invertebrates and fish), forming groups, sometimes accompanying other species. They perform migrations from the feeding to the spawning grounds. Spawning time ranges from spring (North Sea) to late summer (Eastern Baltic). The eggs are pelagic.

([61]) Animals (mollusks) with tentacles converging at the head, around the mouth (squids, cuttlefish, octopus)

European hake (*Merluccius merluccius* L. 1758) North East Atlantic, North Sea, Mediterranean

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
140cm	20 years	demersal, marine; 30-1000m	temperate

Minimum population doubling time: 4.5 – 14 years (low)

European hake are found usually between 70 and 370m depth, whereas the juveniles live in deeper water and move to coastal waters when they grow. Juveniles feed on crustaceans (mainly euphausiids and amphipods), the adults feed mainly on fish. Hake perform spawning migrations from the feeding grounds near the coast to the spawning area in deeper water. Spawning takes place from spring to summer. Eggs are pelagic.

Great sandeel (*Hyperoplus lanceolatus* Le Sauvage 1824) North Sea

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
40cm	25 years	demersal, marine and brackish; 6-30m	temperate

Minimum population doubling time: 1.4 – 4.4 years (medium)

Great sandeels are commonly associated with *Ammodytes* species. Main prey are zooplankton and small fish. Spawning takes place in the summer months. The eggs are sticky and demersal.

Lesser sandeel (*Ammodytes marinus* Raitt 1934) North Sea

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
25cm	10 years	benthopelagic, marine and brackish	temperate

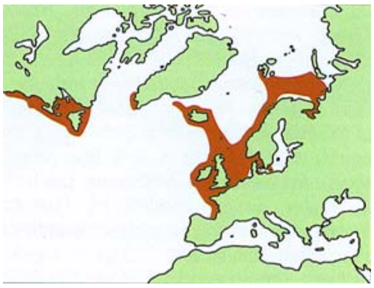
Minimum population doubling time: 1.4 – 4.4 years (medium)

Lesser sandeel form schools and are usually territorial. They are burrowed in sandy grounds during periods of low light intensities (night and winter). Main prey is zooplankton. Spawning takes place during winter and the eggs are attached to the sand.

Haddock (*Melanogrammus aeglefinus* L. 1758) North East Atlantic, North Sea

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
100cm	20 years	demersal, marine; 10-450m	4°C - 10°C

Minimum population doubling time: 1.4 – 4.4 years (medium)

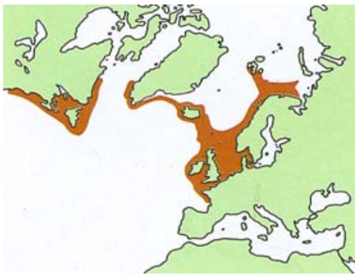


Haddock is commonly found from 80 to 200m over rock, sand, gravel or shells. It feeds mainly on small bottom-living organisms including crustaceans, molluscs, echinoderms, worms and fish. Spawns pelagic eggs in depth of 50-150 m.

Saithe (*Pollachius virens* L. 1758) North East Atlantic, North Sea

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
130cm	25 years	demersal, marine; 0-200m	temperate

Minimum population doubling time: 1.4 – 4.4 years (medium)



Saithe is an active, gregarious([62]) fish occurring in inshore and offshore waters. It usually enters coastal waters in spring and returns to deeper waters in winter. The younger fish inhabits inshore waters and feeds on small crustaceans (copepods, amphipods, euphausiids) and small fish, while the older fish preys predominantly upon fish.

European plaice (*Pleuronectes platessa* L. 1758) North East Atlantic, North Sea

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
100cm	50 years	demersal, marine and brackish; 0-200m	2°C – 15°C

Minimum population doubling time: 4.5 – 14 years (low)

European plaice live on mixed bottom, are active during the night and are buried in sand during the day. Juveniles are found near the coast in shallow water, whereas the older fish stay deeper. They prey mainly on molluscs and polychaetes. Often believed to be stationary, tagging experiments have shown that migration can be performed over large distances. They spawn during late winter and spring and the eggs are pelagic.

([62]) Relating to a social group

Round sardinella (*Sardinella aurita* Valenciennes 1847) Mediterranean

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
31cm	7 years	reef-associated, marine and brackish; 0-350m	subtropical

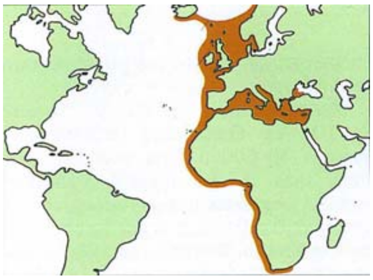
Minimum population doubling time: less then 15 months (high)

Sardinella form schools in coastal waters from inshore to the edge of the shelf. The juveniles stay near the coast in the feeding areas and join the adult population at maturity. Sardinella prey both on benthic crustaceans and zooplankton. Spawning takes place throughout the year with no distinct spawning peak. The eggs are laid in the open water.

Atlantic horse mackerel (*Trachurus trachurus* L, 1758) Atlantic, Mediterranean

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
70 cm	--- years	pelagic, marine (oceanodromous); 0-1050m	15°C – 31°C

Minimum population doubling time: 4.5 – 14 years (low)

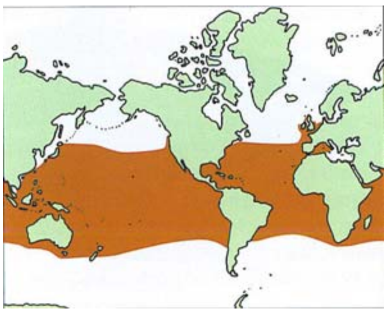


Atlantic horse mackerel form large schools in coastal areas and feed mainly on fish, crustaceans and cephalopods.

Skipjack tuna (*Katsuwonus pelamis* L. 1758) Atlantic, Mediterranean

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
100cm	12 years	pelagic, marine (oceanodromous); 0-260m	15°C – 30°C

Minimum population doubling time: 1.4 – 4.4 years (medium)

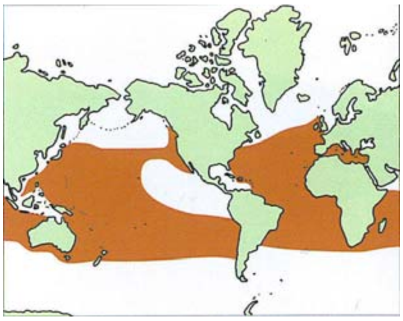


Skipjack tuna are mainly found in offshore waters, with a tendency to school in surface waters. Often found near drifting objects. The eggs are laid in the open water. Larvae are restricted to waters with surface temperatures of 15°C to 30°C. Natural predators are mainly various shark species, Orcas and some birds.

Yellowfin tuna (*Thunnus albacares* Bonnaterre, 1788) Atlantic, Mediterranean

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
240cm	8 years	pelagic, brackish and marine (oceanodromous); 0-250m	15°C – 31°C

Minimum population doubling time: 1.4 – 4.4 years (medium)



Yellowfin tuna is an oceanic species. The individuals school by size. Schools are often found near floating objects. Yellowfin tuna is highly valued for sashimi.

Annex 1-2: Biological characteristics of the biological environment of industrial key fish species

Pseudocalanus acuspes, Baltic Sea

P. acuspes is a boreal species and therefore believed to be adapted to low temperatures and high salinities (Renz und Hirche 2006). It benefits from cold winters and inflow of high saline North Sea water into the Baltic (Möllmann *et al.* 2000, 2003).

Acartia spp. Baltic Sea, North Sea

The genus *Acartia* consists of several species which are found in all areas. In the Baltic Sea *A. bifilosa* and *A. longiremis* are the dominant species. Both species are euryhaline([63]), i.e. they can live in a wide range of salinities. They also benefit from higher temperatures (Möllmann *et al.* 2000, 2003). In the North Sea there are additionally *A. clausi* and *A. tonsa*. *A. clausi* is described as a typical marine species (Hansen 1960) whereas *A. tonsa* is a brackish water species (euryhaline and eurytherme([64])).

Calanus finmarchicus and *Calanus helgolandicus* North East Atlantic, North Sea

C. finmarchicus is a marine species, adapted to cold water, and an indicator species for subarctic water. *C. helgolandicus* is adapted to a temperate environment and is found in oceanic as well as neritic([65]) water. Both species perform daily vertical migration over several hundreds of metres.

Centropages typicus North Sea, Mediterranean

C. typicus is warm water species, typical for the North Sea as well as the Mediterranean (Clark 1933). The minimum breeding temperature is 8°C-12°C (Bigelow 1926).

Temora stylifera North Sea, Mediterranean

T. stylifera is a neritic species, which can also be found in an oceanic environment. It benefits from lower temperatures (Mazza 1961).

Major organisms farmed in Europe are blue mussel, rainbow trout and Atlantic salmon. Northern Europe concentrates on Salmonids, whereas in the Mediterranean diversification is favoured with 40 species being cultivated (Hoepffner 2006). In the following table only marine organisms are listed.

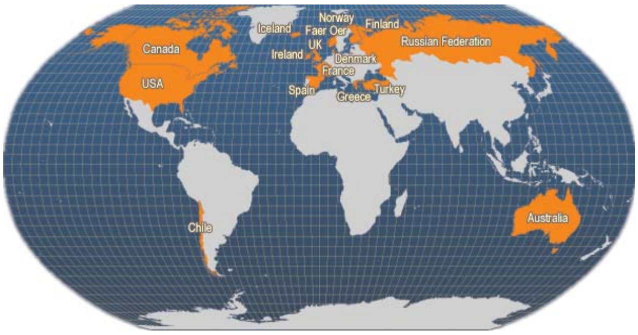
([63]) Organism that lives in a wide range of salinities
([64]) Organism that lives in a wide range of temperatures
([65]) Relates to the ocean domain above the continental shelf and top edge of the continental slope. Corresponds to nearshore waters.

Annex 1-3: Biological characteristics of key species used in marine aquaculture

Atlantic salmon (*Salmo salar* L. 1785)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
150cm	13 years	Pelagic, freshwater, marine and brackish (anadromous); 0-210m	2°C – 9°C

Minimum population doubling time: 1.4 – 4.4 years (medium)



Atlantic salmon is mainly cultured in Norway. In the wild, adults grow in the ocean and migrate back into the rivers where they spawn. The young salmon remain in freshwater for 1-6 years before they migrate to the ocean. Adults in freshwater which are approaching the reproductive stage do not feed.

Gilthead seabream (*Sparus aurata* L. 1785)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
70cm	11 years	demersal, marine and brackish (anadromous); 0-150m	Subtropical, > 4°C

Minimum population doubling time: 1.4 – 4.4 years (medium)

Gilthead seabream is mainly cultured in Spain, Italy and Greece. It is characterized as euryhaline and eurythermal, i.e. it can withstand a high range of salinities and temperatures. Although only its lower temperature limit is mentioned in the literature, an upper temperature limit is assumed to be at ca. 26°C when the fish stops feeding and mortality increases dramatically.

European seabass (*Dicentrarchus labrax* L. 1785)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
100cm	15 years	demersal, freshwater, marine and brackish (anadromous); 10-100m	Subtropical, 8-24°C

Minimum population doubling time: 1.4 – 4.4 years (medium)

European seabass is mainly cultured in Spain, Italy and Greece. It is characterized as euryhaline and eurythermal, i.e. it can withstand a high range of salinities and temperatures.

Blue mussel (*Mytilus edulis* L. 1785)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
cm	24 years	Benthic, marine and brackish, intertidal to subtidal	5°C – 20°C

M. edulis has a wide distributional pattern, mainly due to its abilities to withstand wide fluctuations in salinity, desiccation, temperature, and oxygen tension. Although blue mussels can live up to 18-24 years, most cultured mussels are produced in less than 2 years.

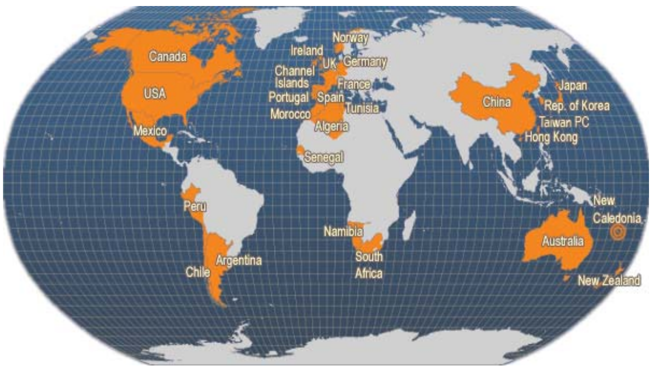
Mediterranean mussel (*Mytilus galloprovincialis* Lamark 1819)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
---	---	Benthic, marine and brackish, intertidal to subtidal	5°C – 20°C

Up to the early 1990s, all mussels from Western Europe were considered to be *Mytilus edulis*. It is now known that the mussels from southern Brittany (France) to the Mediterranean Sea are *M. galloprovincialis*.

Pacific oyster (*Crassostrea gigas* Thunberg 1793)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
---	---	Benthic, marine and brackish, 0-40m	-1.8°C – 35°C



Optimal salinity range is between 20 and 25‰ although the species can occur at salinities below 10‰ and will survive salinities in excess of 35‰, where it is unlikely to breed. Although the oyster can survive a wide range of temperatures, spawning generally occurs at temperatures above 20°C and rarely at 15–18°C. Growth rate is very rapid in good conditions; market size being attained in 18 to 30 months.

Japanese carpet shell (*Ruditapes philippinarum* Adams & Reeve, 1850)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
---	---	marine	Subtropical to low boreal

Although the Japanese carpet shell can survive a wide range of temperatures, spawning generally occurs at temperatures between 20 and 25°C. Lower temperature limit is 12°C. Growth rate is very rapid in good conditions; market size being attained in 18 to 36 months.

Rainbow trout (*Oncorhynchus mykiss* Walbaum , 1792)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
120cm	11 years	benthopelagic, freshwater, marine and brackish (anadromous); 0-200m	0°C – 27°C

Minimum population doubling time: 1.4 – 4.4 years (medium)

Rainbow trout is a very common cultured species. It can withstand a high temperature range, although the optimum for spawning and growth lies between 9-14°C. The culture temperature is usually below 21°C.

Turbot (*Psetta maxima* L , 1758)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
100cm	25 years	demersal, marine and brackish (oceanodromous); 20-70m	temperate

Minimum population doubling time: 1.4 – 4.4 years (medium)

Although the main production of turbot is in Europe, the species was introduced to Chile and more recently to China. The optimal temperature range for cultivation lies between 14°C and 18°C. Market size could be attained in 24 to 30 months.

Grooved carpet shell (*Ruditapes decussatus* L, 1758)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
---	---	marine	Subtropical to low boreal

The grooved carpet shell is cultured from the Atlantic coast of France, Spain, Portugal and in the Mediterranean basin. This species needs sandy habitat to live. Market size could be attained in 18 to 36 months.

European flat oyster (*Ostrea edulis* L, 1758)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
---	---	brackish, marine	Temperate, 10°C to 25°C

The European flat oyster is a native of Europe. It is cultured from the UK to Greece. The oyster can withstand salinities as low as 15‰; salinities of about 20‰ are optimal for larval growth.

European eel (*Anguilla anguilla* L , 1758)

Max. size	Max. age	Environment (water zone, type and depth)	Temp. range
130cm	85 years	demersal, freshwater, marine and brackish (catadromous); 0-700 m	Temperate, 4°C – 24°C

Minimum population doubling time: >14 years (very low)

Currently, the top three producing countries of farmed European eels are the Netherlands, Italy and Denmark. Production of eels is based on wild catches of glass eels (elvers) used for further ongrowing. Extensive culture of European eels under natural conditions has diminished to a level of no commercial importance. Intensive production by the use of recirculation technology, keeping water temperatures stable around 24°C, has become the overall production method.

Annex 2. Documentation of the results of literature research

Reference	serial	related to	sub-chapter	keyword	remark	Area	Species
ACIA 2005	1981	other	4.3.3	primary production and climate		North Atlantic	general
Alheit & Hagen 1997	1821	water	4.1.6	NAO, herring, sardine	switch	North Atlantic, North Sea	herring, sardine
Alheit *et al.* 2005	1169	fish	4.2.6	regime shift	change	North Sea, Baltic Sea	cod,sprat, herring, copepods
Araujo & New 2007	1711	Fish	4.2.3	temperature	change	global	general
Araujo *et al.* 2005	1747	Fish	4.2.3	temperature	change	global	general
Arnell 1998	1923	other	4.2.7	water resources, climate impact	change	North Sea, Britain	
Arnott & Ruxton 2002	1773	Fish	4.2.3	fish recruitment, NAO	shift in distribution; recruitment dependend on calanus	North Sea	sandeel
Arnott & Ruxton 2002	1773	Other	4.3.7	fish recruitment NAO	shift in distribution; recruitment dependend on calanus	North Sea	sandeel
Astraldi *et al.* 1995	1988	other	4.3.6	species distribution	change	Mediterranean	
Attrill & Power 2002	1814	Fish	4.2.2	NAO	change	Themse estuary	general
Attrill *et al.* 2007	1805	Fish	4.3.1	jellyfish	rise	North Sea	jellyfish
Attrill *et al.* 2007	1805	Fish	4.3.7	jellyfish	rise	North Sea	jellyfish
BACC 2006	1980	water	4.1.5	change in temperature, salinity		Baltic	genaral
Basilone *et al.* 2006	1818	Fish	4.2.5	temperature	timing of spawning	Strait of Sicily	anchovy
Beare *et al.* 2002	1876	water other	4.1.2	calanus temperature salinity stratification, inflow		North sea	Calanus
Beare et al. 2004a	1843	fish	4.1.3	temperature	distribution	North Sea	general
Beare et al. 2004a	1843	fish	4.2.2	temperature	distribution	North Sea	general
Beare *et al.* 2004b	1842	fish	4.1.3	distribution shift of sardine and anchovy in North Sea	increase in temperature; invasion of species normally not there	North Sea	sardine, anchovy
Beaugrand 2004	1924	Fish	4.3.6	regime shift		North Sea	general
Beaugrand *et al.* 2002	1802	Zooplankton	4.3.7	temperature	rise	North Sea	copepods
Beaugrand *et al.* 2003	374	Fish	4.2.6	recruitment cod zooplankton larval cod survival	match/mismatch; bottom up control	North Sea	cod
Beaugrand *et al.* 2003	374	Fish, Other	4.3.3	recruitment cod zooplankton larval cod survival	match/mismatch; bottom up control	North Sea	cod
Beaugrand *et al.* 2003	374	Fish, Other	4.3.4	recruitment cod zooplankton larval cod survival	match/mismatch; bottom up control	North Sea	cod
Beaugrand *et al.* 2003	374	Fish, Other	4.3.7	recruitment cod zooplankton larval cod survival	match/mismatch; bottom up control	North Sea	cod
Behrenfeld et al. 2006	2061	water	3.1.3	stratification	global warming	global	
Behrenfeld et al. 2006	2061	other	3.3.3	productivity high latitude	decline	global	
Berkeley *et al.* 2004	575	Fish, Other	4.3.4	maternal effect	keep the old ones	global	rockfish

Reference	**serial**	**related to**	**sub-chapter**	**keyword**	**remark**	**Area**	**Species**
Bethoux *et al.* 1999	1905	others	4.1.5	mediterranean special system review			
Bethoux *et al.* 2002	1920	water	4.1.3	NAO effect on phytoplanktonswitch		Mediterranean	plankton
Bigelow 1928	1998	other	4.3.1	temperature	breeding	Gulf of Maine	Centropages
Birkeland & Dayton 2005	1837	Fish, Other	4.3.4	maternal effect	keep the old ones	global	general
Bjornsson & Steinarsson 2002	1886	fish	4.2.4	temperature growth experiments	dome-shape relationship	global	cod
Bombace 2001	1778	fish	4.2.2	distribution shift	change	Mediterranean	sprat, mackerel
Brander 1994	2017	fish	4.2.4	temperture	growth rate	North Sea	cod
Brander 1995	1891	fish	4.2.2	temperature and growth, bottom temperature	change	Atlantic, North Sea	cod
Brander 2006	1925	fish	4.1.3	temperature & stratification	judgement of models	global	general
Brander 2006	1925	others	4.3.3	temperature & stratification	judgement of models	global	general
Brander *et al.* 2003	1752	Zooplankton	4.3.7	temperature	rise	North Sea	copepods
Brett 1956	1926	fish	4.2.1	temperature physiology, ecology	reaction to temperature change	global	general
Browman *et al.* 2000	1726	Fish, Other	4.2.7	evolutionary changes caused by fishing	life history responses, phenotypic plasticity, selection for faster growth	global	general
Brown 2003	1927	fish	4.2.1	temperature detection in fish	physiology	global	shark
Bryden *et al.* 2005	1824	Water	4.1.2	thermohaline circulation	decrease in circulation	North East Atlantic	thermohaline circulation
Buecher 1999	2002	other	4.3.6	long term fluctuations jellyfish	change	Mediterranean	jellyfish
Burton 1979	1928	fish	4.2.1	temperature and ventilation	physiology	global	estuarine fish
Caldeira & Wickett 2003	1855	other	4.1.1	ocean acidification	pH changes larger than from fossil records	global	general
Caldeira & Wickett 2005	1854	other	4.1.1.	ocean acidification	predicted ph changes	global	general
Carotenuto *et al.* 2006	1997	other	4.3.6	population dynamics of copepods		Mediterranean	copepods
Casini *et al.* 2006	1801	Fish	4.2.5	prey	change	Baltic Sea	herring, sprat
Cayan 1992	1982	water	4.1.6	thermodynamic forcing effect on sea surface tempertaures		global	NAO
Chavez *et al.* 2003	2054	fish	3.2.6	Regime shift	ecosystem change	pacific	anchovy, sardine
Chavez *et al.* 2003	2054	water	3.1.6	temperature	ecosystem change	pacific	
Ciais *et al.* 2005	2057	water	3.1.1	temperature	heat wave, climate change	Europe	
Ciannelli *et al.* 2005	1751	Fish	4.2.7	temperature	rise	Pacific	walleye pollock
Clark *et al.* 2003	1863	fish	4.2.4	model cod and climate change North Sea		North Sea	cod
Clarke 1993	1929	Fish	4.2.1	temperature distribution limit, extinction risk	physiology	global	general
Claussen *et al.* 2003	1826	Water	4.1.2	shift in thermal equator	change	global	general
Collie *et al.* 2004	1914	fish	4.2.6	internal changes in ecosystems	regime shifts	global	general

Reference	**serial**	**related to**	**sub-chapter**	**keyword**	**remark**	**Area**	**Species**
Cook *et al.* 1997	1730	fish	4.3.7	overexploitation, collapse in cod stocks	decline in cod	North Sea	cod
Coutant 1987	1930	fish	4.2.1	temperature selection, thermal preference behavour		global	general
Curry & Mauritzen 2005	1823	water	4.1.1	dlilution of the North Atlantic, salinity	change	North Atlantic	
Cushing 1984	1887	other	4.1.6	gadoid outburst	NAO	North Sea	gadoids
Cushing 1990	1844	other	4.3.3	match/mismatch	plankton fish interactions	North Sea	general
Davis *et al.* 1998	1931	fish	4.2.6	climate envelop, species interaction	change		Drosophila
Dickson & Brander 1993	1932	fish	4.2.3	cod stock distribution, environmetal effect	change	North Atlantic	cod
Drinkwater 2005	1869	fish	4.2.2	cod recruitment, distribution & temperature	cod stock comparison, predictions	North Atlantic	cod
Drinkwater 2005	1869	fish	4.3.4	cod recruitment, distribution & temperature	cod stock comparison, predictions	North Atlantic	cod
Drinkwater 2006	1867	fish	4.2.3	migration 1920 1930 regime shift		Atlantic	cod
Dulcic *et al.* 1999	1781	fish	4.2.2	reduction in cold water species, new and warm water species invasion	distribution shift	Mediterranean	sprat, mackerel
Dutil & Brander 2003	788	fish	4.2.2.	temperature optimum cod	effect on distribution	North Sea, North Atlantic	cod
Edwards & Richardson 2004	1719	other	4.3.7	phenology, mismatch	shift in timing	North Sea	phyto-, zoo-, meroplankton
Edwards & Richardson 2004	1719	Plankton	4.3.3	temperature	rise	North Sea	plankton
Edwards *et al.* 2001	1803	Phyto-plankton	4.3.7	invasion	anthropogenic	North Sea	Coscinodiscus wailesii
Edwards *et al.* 2002	1804	Zooplankton	4.3.7	NAO	change	North Sea	plankton
Eisenreich 2005	2011	water	4.1.1.	salinity and climate	change	Mediterranean	
Engelhard & Heino 2004	1838	fish	4.2.5	temperature fish condition skipped reproduction	high temperature; skipped reproduction; Norwegian herring	Atlantic	herring
Engelhard & Heino 2004	1838	fish	4.2.7	temperature fish condition skipped reproduction	high temperature; skipped reproduction; Norwegian herring	Atlantic	herring
Engelhard & Heino 2006	1878	fish	4.2.5	climate skip spawning		North Atlantic	herring
ESA	1921	fish	4.3.5	climate	fisheries	global	general
Feely *et al.* 2004	1853	Other	4.1.1	Ocean acidification	effect of increased CO2 decreased pH	global	general
Ferguson 1958	1933	fish	4.2.1	temperature effect on ecology and physiology		lakes, streams	
Fernandez *et al.* 2003	1987	other	4.3.6	sea level changes		Mediterranean	

Reference	serial	related to	sub-chapter	keyword	remark	Area	Species
Fox *et al.* 2000	2020	fish	4.3.7	temperature	recruitment variability	North Sea	plaice
Francour *et al.* 1994	1779	fish	4.2.2	warm fish in cold biota		Mediterranean	
Frank *et al.* 2005	1104	fish	4.3.4	effect of removal of top predator, restructuring of food web	effects of fishing	North Atlantic	cod
Froese & Pauly 2007	2017	fish	4.2.1	Fish data base		global	general
Fromentin & Planque 1996	1934	fish	4.2.5	relationship NAO and temperature and copepods	change	North Sea	
Fry 1947	2017	fish	4.2.1	temperature physiology, ecology	reaction to temperature change	global	general
Fry 1971	1935	fish	4.2.1	temperature physiology, ecology	reaction to temperature change	global	general
Garcia *et al.* 2003	1444	fish	4.3.5	climate change	fisheries	global	general
Gaylord & Gaines 2000	1857	other	4.2.3	transport vs temperature important for distribution		global	general
Genner *et al.* 2004	1841	fish	4.2.2.	temperature fish distribution change	interaction effects	North Sea	many species
Goffart *et al.* 2002	1993	other	4.3.6	phytoplankton bloom	change	Mediterranean	phytoplankton
Gomez & Gorsky 2003	1994	other	4.3.6	microzooplankton cycles	change	Mediterranean	
Gomis *et al.* 2006	1911	water	4.1.6	NAO, sea level variability, salinity		Mediterranean	
Goren & Galil 2005	1807	Fish	4.3.2	Invasion	anthropogenic	Levantine Sea	fish
Goy *et al.* 1989	2001	other	4.3.6	long term fluctuations jellyfish	change	Mediterranean	jellyfish
Greene & Pershing 2007	2055	other	3.3.3	productivity high latitude	increase	Arctic	
Guisande *et al.* 2004	1817	Fish	4.3.3	temperature	change	Central Atlantic Mediterranean	sardine
Halsband-Lenk & Hirche 2001	1999	other	4.3.6	seasonal production cycles	change	North Sea	copepods
Hannesson 2007	1799	Fish	4.2.2	temperature	rise	North East Atlantic	cod, mackerel, sardine
Hänninen *et al.* 2000	234	other	4.3.6	Temperature, salinity, NAO	change	Baltic	
Hansen 1960	1995	other	4.3.1	distribution		Norwegian Sea	Acartia
Harley *et al.* 2006	1840	Fish, Other	4.2.6	review climate change effects on coastal marine ecosystems, mainly benthic	importance of interactions, conclusions	global	general
Harley *et al.* 2006	1840	Fish, Other	4.2.7	review climate change effects on coastal marine ecosystems, mainly benthic	importance of interactions, conclusions	global	general
Harrods *et al.* 2007	1936	water	4.1.2	Climate & fisheries, around British Isles	review	North Sea, North Atlantic	general
Harrods *et al.* 2007	1936	fish	4.2.1	Climate & fisheries, around British Isles	review	North Sea, North Atlantic	general
Harvell *et al.* 1999	1877	other	4.2.7	climate and disease outbreak		global	general
Harwood & Stokes 2003	1754	General	conclu-sion	complexity			model
Hauser *et al.* 2002	1937	fish, other	4.3.4	effects of overfishing on genetic diversity	loss of diversity	New Zealand	snapper

Reference	serial	related to	sub-chapter	keyword	remark	Area	Species
Hawkins *et al.* 2003	1753	All	4.2.2	temperature	change	English Channel	all
Hawkins *et al.* 2003	1753	All	4.3.7	temperature	change	English Channel	all
Hays *et al.* 2005	1740	Zooplankton	4.3.3	temperature	rise	North East Atlantic	zooplankton
Hays *et al.* 2005	1740	Zooplankton	4.3.7	temperature	rise	North East Atlantic	zooplankton
Helmuth *et al. 2006*	1852	other	4.3.2	biological invasion	role of environmental variability	intertidal ecosystems	
Henderson 1998	2019	fish	4.3.7	temperature	recruitment variability	North Sea	dab
Herrick *et al.* 2007	1813	Fish	conclu-sion	climate	change	Pacific	sardine
Hjermann et al 2007	1798	Fish	4.2.2	temperature	change	North East Atlantic	cod
Hjermann et al 2007	1798	Fish	4.3.1	temperature	change	North East Atlantic	cod
Hjort 1914	23	fish, other	4.3.7	match mismatch	recruitment variability	North Sea , North Atlantic	cod
Hochachka & Somero 2002	1856	other	4.2.1	biochemical adaptations to temperature		global	general
Hoepffner *et al.* 2006	1938	other	4.3.1	climate change marine and coastal dimensions	review	European waters	
Hoepffner *et al.* 2006	1938	other	4.3.7	climate change marine and coastal dimensions	review	European waters	
Hoepffner *et al.* 2006	1938	water	4.1.5	climate change marine and coastal dimensions	review	European waters	
Hoepffner *et al.* 2006	1938	other	4.3.3	climate change marine and coastal dimensions	review	European waters	
Holbrook *et al.* 1997	1939	fish	4.2.2.	shift of fish distribution in temperate reef	change	North Atlantic	general
Houghton *et al.* 2001	1940	water	4.1.1.	climate change is real, increase in greenhouse gases		global	general
Hsieh *et al.* 2006	1723	other	4.3.4	effects of fishing and environmental variability		california Current	larval fish
Hulme *et al.* 2002	1941	water	4.1.1.	climate change is real, increase in greenhouse gases		Global	general
Hurrell *et al.* 2006	2012	water	4.1.6	NAO	effect of NAO on temperatures and precipitation	global	
Hurrell & Dickson 2004	1943	water	4.1.6	NAO index	effect of NAO on temperatures and precipitation	global	general
Hurrell 1995	1942	water	4.1.6	NAO index	effect of NAO on temperatures and precipitation	global	general
Ianora *et al.* 2003	1996	other	4.3.6	effect of diatoms on copepod reproduction		global	
ICES 2006	2006	water	4.1.2	boundary conditions	change	North Atlantic, North Sea, Baltic Sea	

Reference	serial	related to	sub-chapter	keyword	remark	Area	Species
IPCC report 2007	2007	water	4.1.1.	climate change predictions		global	general
Iversen *et al.* 2002	1835	Fish	4.2.5	climate	change	North Sea	horse mackerel
James 1988	1990	fish	4.2.1	prey		Mediterranean	anchovy
Javidpour *et al.* 2006	1979	other	4.1.5	Invasion	change	Baltic	jellyfish
Jensen 1939 as cited in Drinkwater 2006	1867	fish	4.2.3	distribution shift	northward shift in relation to temperature and prey	North Atlantic	cod
Jensen 2003	2023	fish	4.2.2	temperature	distribution and growth	North America	salmon
Jobling 1981	1945	fish	4.2.1	lethal temperature limits	temperature tolerance	global	general
Jobling 1997	1944	fish	4.2.1	fish thermal conformers, thermal regulation, temperature selection	effect of temperature on growth	global	general
Jones *et al.* 1997	1948	water	4.1.6	NAO index	effect of NAO on temperatures and precipitation	global	general
Jurado-Molina & Livingstone 2002	1865	fish	4.2.4	population model simulations, recruitment, climate forcing	include environmental effects	global	groundfish
Karl & Trenberth 2003	1972	water	4.1.1	increase in global temperature		global	general
Kent & Poppe 1998	2022	fish	4.3.8	clima	diseases	global	general
Kiehl & Trenberth 1997	1947	water	4.1.1	greenhouse gas increase	increased retain of radiation	global	general
King 2004	1946	water	4.1.1	increase in global temperature	rsik analysis forcast	global	general
Kirby *et al.* 2006	1775	Fish	4.3.4	temperature and occurrance, increased larval and juvenile survival	increase in abundance since 2002	North Eastern Atlantic	snake pipefish
Kirby *et al.* 2007	1839	Fish Other	4.3.7	temperature bentho-pelagic coupling	increase in meroplankton (Echinocardium) due to warmer temperature conditions in winter and spring	North Sea	meroplankton, holozooplankton
Klyashtorin 1998	1748	Fish	conclu-sion	atmospheric circulation index		global	general
Klyashtorin 2001	1750	Fish	4.3.5	temperature	change	global	general
Köster *et al.* 2003	271	other	4.3.6	temperature, salinity, species composition	change	Baltic	fish, zpooplankton
Köster *et al.* 2005	1430	fish	4.2.6	regime shift	shift in plankton and fish abundance and relationship	Baltic Sea	plankton, fish
Lehodey *et al.* 2006	1894	fish others	conclu-sion	fish fisheries and climate	conclusions	global	general
Lehtonen 1996	2005	other	4.3.8	temperature	food conversion	Baltic Sea	Monoporeia
Levermann *et al.* 2005	1825	water	4.1.2	global sea level	change	Global	general
Levitus *et al.* 2000	1973	water	4.1.1	warming marine and freshwater systems	change	Global	general
Maes *et al.* 2005	1815	Fish	4.2.1	temperature	change	North Sea	herring
Magnuson *et al.* 1979	1974	fish	4.2.1	selection of thermal habitat	strategy maximize growth		fish

Reference	**serial**	**related to**	**sub-chapter**	**keyword**	**remark**	**Area**	**Species**
Malacic *et al.* 2006	1780	fish	4.1.1	temperature, salinity change		Mediterranean	
Malzahn et al. 2007	2063	others	3.3.7	match/mismatch	food quality	Baltic	herring
Maravelias & Reid 1995	1741	Fish	4.2.1	temperature	change	North Sea	herring
Maravelias & Reid 1995	1741	Fish	4.2.2	temperature	change	North Sea	herring
Maravelias & Reid 1995	1741	Fish	4.2.3	temperature	change	North Sea	herring
Marteinsdottir & Steinarsson 1998	699	other	4.3.4	larger fish produce larger eggs	effect on recruitment	Iceland	cod
Marty & Chiaverini 2002	1919	water	4.1.3	NAO effect on phytoplankton; switch		Mediterranean	plankton
Mazza 1961	2000	other	4.3.1	temperature		Mediterranean	Temora
McCarty 2001	1746	General	conclu-sion	climate	change	global	general
MCCIP 2006	2008	water	4.1.3	stratification North Sea	increase	North Sea	
MCCIP 2006	2008	other	4.3.2	invasions of organisms	increase	North Sea	
MCCIP 2006	2008	other	4.3.8	climate effect on aquaculture		global	general
McGoodwin 2007	1811	Fish	conclu-sion	climate	variability	Alaska	general
Medina *et al.* 2002	1896	fish	4.2.5	gonad maturation temperature		Mediterranean	tuna
Menard & Fromentin 1997	2004	other	4.3.6	temporal fluctuations of doliolid	change	Mediterranean	
Menard *et al.* 1994	2003	other	4.3.6	temporal fluctuations of salp	change	Mediterranean	salp
Miller & Munro 2004	2021	fish	4.3.5	climate variability	management	Pacific	salmon
Miller 2007	1812	fish	4.3.5	climate variability	management	Pacific	tuna
Mills & Mann 1985	1975	fish	4.2.1	temperature effect of populations, ecological effects			
Misund *et al.* 1998	1738	Fish	4.2.2	temperature	change	North Sea	herring
Misund *et al.* 1998	1738	Fish	4.2.5	temperature	change	North Sea	herring
Molinero *et al.* 2005a	1783	other	4.3.6	zooplankton phenology	change	Mediterranean	plankton
Molinero *et al.* 2005b	1784	other	4.1.3	NAO, plankton	change	Mediterranean	plankton
Molinero *et al.* 2005b	1784	other	4.3.6	NAO, plankton	change	Mediterranean	plankton
Molinero *et al.* 2007	1983	water	4.1.4	shift in copepod abundance	phenology and productivity	Mediterranean	plankton
Molinero *et al.* 2007	1983	other	4.3.6	climate change ecological effect	food web change	Mediterranean	general
Möllmann *et al.* 2000	205	other	4.3.1	temperature		Baltic Sea	Pseudocalanus, Acartia
Möllmann *et al.* 2003	277	other	4.3.6	swich in dominance of Copepods		Baltic	plankton
Moore *et al.* 1997	1949	fish	4.2.7	increase in temperature, higher mobility of contaminants		Freshwater ecosystems, mid Atlantic	
Muus and Nielsen 1999	1986	fish	4.2.1	distribution		North East Atlantic	general
Naylor *et al.* 2000	1913	other	4.3.8	aquaculture effect on eutrophication		Global	general

Reference	serial	related to	sub-chapter	keyword	remark	Area	Species
Nehring 2003	1806	Other	4.3.2	invasion	anthropogenic	North Sea, Baltic Sea	general
O'Brien *et al.* 2000	1950	fish	4.3.4	temperature effect on cod recruitment		North Sea	cod
Olsen *et al.* 2004	221	Fish	4.3.4	fishing pressure reduces size and fecundity		North Atlantic	cod
Orr et al. 2005	2052	water	3.1.1	acidification	increase	Global	
Ottersen *et al.* 2001	1736	fish others	4.1.6	NAO, ecological effects		global	general
Parmesan & Yohe 2003	1731	fish other	4.2.2	Metaanalysis shift indifferent species	northern distribution shift, earleier spring	global	general
Parmesan 2006	1951	other	4.2.2	phenology, abundance, distribution	change	Global	general
Parmesan *et al.* 2005	1830	General	conclu-sion	climate	change	global	general
Parsons & Lear 2001	1820	Water	4.1.6	NAO	effect on biosphere	North Atlantic	fish
Patz *et al.* 2005	2051	water	3.1.1	temperature	heat wave, climate change	Europe	
Pauly *et al*. 2005	1348	Fish	4.3.4	Fishing	negative effect on fish	Global	fish
Pawlak et al. 2007	2062	water	3.1.5	temperature, salinity	global warming	Baltic	
Pearson & Dawson 2003	1866	other	4.2.3	bioclimate envelope	species distribution change	Global	general
Perry *et al.* 2005	1718	Fish	4.2.2	climate	change	North Sea	general
Perry *et al.* 2005	1718	Fish	4.2.3	climate	change	North Sea	general
Persson 1986	1952	Fish	4.2.1	temperature	impact on community	Lake	roach, perch
Peterson et al. 2006	2060	water	3.1.1	salinity	decrease	Arctic	
Planque & Fox 1998	1889	Fish	4.1.6	temperature	higher metabolic rates reduced recruitment	North Atlantic	cod
Planque & Fredou 1999	1978	fish	4.3.4	temperature recruitment relationship		North Atlantic North Sea	cod
Poloczanska et al 2004	1816	Fish	4.3.5	fishing	change	North Sea	sandeel
Polovina 2005	1832	Fish	4.3.4	climate change	regime shift due to influence on apex predators	North Pacific	general
Pope & Symes	2018	Fish	4.3.5	ecosystem approach to fisheries		global	general
Pörtner & Knust 2007	1899	fish others	4.2.1	temperature and metabolism	effect on distribution		
Pörtner 2002	1953	Fish	4.2.7	temperature	metbolism	Northern Latitude	general
Pörtner *et al.* 2004	1954	Fish	4.2.7	temperature	respiration	global	general
Pörtner *et al.* 2005	1861	fish	4.2.1	Combined effect of temperature, pH, physiology	conclusion	global	general
Rahmstorf 2000	1744	Water	4.1.1	climate	change of thermohaline circulation	North Atlantic	
Rahmstorf 2002	1822	water	4.1.2	climate change	changing circulation	North Atlantic	
Raper *et al.* 1997	1955	water	4.1.1	greenhouse gas increase		British Isles	

Reference	serial	related to	sub-chapter	keyword	remark	Area	Species
Ravier & Fromentin 2004	1892	Fish	4.2.5	temperature	opportunistic homing	Atlantic	tuna
Regier *et al.* 1990	1956	Fish	4.2.1	temperature	physiology	global	general
Renz & Hirche 2006	1064	other	4.3.1	salinity		Baltic Sea	Pseudocalanus
Reynolds & Casterlin 1977	1957	Fish	4.2.1	temperature	behaviour	global	general
Riebesell *et al* . 2000	2053	water	3.1.1	acidification	increase	global	phytoplankton
Rixen *et al.* 2005	1985	other	4.3.6	NAO effects		Mediterranean	
Rodwell *et al.* 1999	1728	water	4.1.1	NAO	sea surface temperature	North Atlantic	
Rogers 1984	1598	water	4.1.1	NAO	index	North Atlantic	
Root *et al.* 2003	1959	Fish	4.2.2	temperature	distribution change	global	general
Rose 2005	1918	fish	4.2.2	distribution shift	temperature effect	North Atlantic	fish
Ruddiman & Thomson 2001	1960	water	4.1.1	greenhouse gas increase	global warming	global	
Sabine *et al.* 2004	1908	water	4.1.1	acidification	increase	global	
Sarmiento *et al.* 2004	1737	other	4.3.3	climate change	productivity	global	phytoplankton
Scavia *et al.* 2002	1862	water	4.1.2	climate change	change in key oceanographic features	global	
Scavia *et al.* 2002	1862	water	4.1.3	climate change	stratification	global	nutrients
Schär *et al.* 2004	2058	water	3.1.1	temperature	heat wave, climate change	Europe	
Schrank 2007	1808	Fish	conclu-sion	climate	change	Arctic	general
Send *et al* . 1999	1903	water	4.1.6	NAO	temperature and salinity	mediterranean	
Sharp 2003	1961	fish	4.1.1	climate change	regional fisheries	global	general
Sheppard 2004	1900	others	4.1.5	temperature increase North sea water	1871-2099 time series		
Siegenthaler *et al.* 2005	1962	water	4.1.1	greenhouse gas increase	global warming	global	
Sims *et al.* 2006	1963	fish	4.2.1	temperature	physiology	global	dogfish
Sirabella *et al* . 2001	1888	fish	4.1.6	NAO	cod recruitment	North Atlantic	cod
Sissener & Bjoerndal 2005	1745	Fish	4.2.5	climate	change	North Sea	herring
Smetacek & Nicol 2005	2056	other	3.3.3	productivity high latitude	increase	Arctic, Antarctica	
Somarakis *et al.* 2006	1819	Fish	4.3.3	climate	change	Mediterranean	sardine
Southward *et al.* 1988	1964	fish	4.2.1	temperature	fish community	North Sea	herring, pilchard
Southward *et al.* 1995	1834	Fish	4.2.2	temperature	rise	North Sea	general
Spahni *et al.* 2005	1965	water	4.1.1	greenhouse gas increase	global warming	global	
Steele 2004	1898	fish	4.2.6	fishing	ecosystem or regime shift	global	general
Stenevik & Sundby 2007	1809	Fish	4.2.4	climate	change	North Sea	general
Stenevik & Sundby 2007	1809	Fish	4.3.8	climate	change	North Sea	general
Stenseth *et al.* 2002	1729	other	4.3.3	climate change	phenology and productivity	North Atlantic and Pacific	
Stenseth *et al.* 2003	1742	Water	4.1.1	climate	change	global	climate indices
Stott *et al.* 2004	2059	water	3.1.1	temperature	heat wave, climate change	Europe	

Table 7: Documentation of the results of literature research

Reference	serial	related to	sub-chapter	keyword	remark	Area	Species
The Royal Society 2005	1966	water	4.1.1	ocean acidification	decrease in calcification	global	phytoplankton
60	1907	water	4.1.5	temperature and salinity	deep water formation	mediterranean	
60	1749	Fish	4.3.5	climate	change	global	general
Tonn 1990	1755	Fish	4.2.5	climate	change	lake	feneral
Trigo *et al.* 2000	1984	other	4.3.6	salinity increase		Mediterranean	
Tsimplis & Josey 2001	1992	other	4.3.6	circulation, NAO	change	Mediterranean	
Tsimplis *et al*. 2006	1909	water	4.1.5	climate change	sea level	mediterranean	
Turrell *et al.* 1992	1967	water	4.1.5	salinity		North Sea	
Veizer, 2005	1968	water	4.1.1	climate change	greenhouse gas vs. solar increase	global	
Vignudelli *et al.* 1999	1991	other	4.3.6	circulation, NAO	change	Mediterranean	
Vilhjalmsson 1997	1976	fish	4.2.5	climate change	migration	North East Atlantic	herring
Visbeck *et al.* 2001	1739	Water	4.1.1	climate	change in NAO	North Atlantic	
Vitousek, 1994	1969	water	4.1.1	climate change	ecosystem change	global	
Walther *et al.* 2002	1743	Fish	conclu-sion	climate	change	global	general
Walther *et al.* 2005	1970	water	4.1.1	climate change		global	
Wang & Overgaard 2007	1770	Fish, Other	4.2.7	temperature and physiological mechanisms	pejus temperature thermal limits, oxygen transport system	global	general
WBGU Report 2006	2009	water	4.1.2	thermohaline circulation	possible change	North Atlantic	
WBGU Report 2006	2009	other	4.3.5	effects of overfishing		North Atlantic	general
Weiss 1970	1977	other	4.2.7	oxygen solubility	temperature effect	global	
Whitehead *et al.* 1988	1989	fish	4.2.1	distribution		Mediterranean	anchovy
Wieland *et al*. 1994	267	fish	4.2.6	salinity and oxygen	buoyancy of eggs	Baltic Sea	cod
Wiltshire & Manly 2004	1901	others	4.1.5	temperature increase	North sea water	North Sea	
Winder & Schindler 2004	1971	water	4.1.1	temperature	freshwater	global	
Wonham *et al.* 2000	1858	fish	4.3.2	Fish introduction via ballast water	Invasive species	global	general
Worm & Myers 2003	1831	fish	4.3.4	overfishing	stock decline	global	general

Bibliography

1. ACIA (2005) Artic Climate Impact Assessment. Cambridge University press 1042 pp.
2. Alheit, J, Hagen, E (1997) Long-term climate forcing of European herring and sardine populations. Fish Oceanogr 6(2): 130-139.
3. Alheit, J, Möllmann, C, Dutz, J, Kornilovs, G, Loewe, P, Mohrholz, V, Wasmund, N (2005) Synchronous ecological regime shifts in the central Baltic and the North Sea in the late 1980s. ICES Journ Mar Sci (62): 1205-1215.
4. Araujo, MB, New, M (2007) Ensemble forecasting of species distributions. Trends Ecol Evol 22(1): 42-47.
5. Araujo, MB, Pearson, RG, Thuiller, W, Erhard, M (2005) Validation of species-climate impact models under climate change. Glob Change Biol 11(9): 504-1513.
6. Arnell, NW (1998) Climate change and water resources in Britain. Clim Change 39(1): 83-110.
7. Arnott, SA, Ruxton, GD (2002) Sandeel recruitment in the North Sea: Demographic, climatic and trophic effects. Mar Ecol Prog Ser 238: 199-210.
8. Astraldi, M-F, Bianchi, CN, Gasparini, GP, Morri, C (1995) Climatic fluctuations, current variability and marine species distribution: A case study in the Ligurian Sea (north-west Mediterranean). Oceanol Acta 18(2): 139-149.
9. Attrill, MJ, Power, M (2002) Climatic influence on a marine fish assemblage. Nature 417(6886): 275-278.
10. Attrill, MJ, Wright, J, Edwards, M (2007) Climate-related increases in jellyfish frequency suggest a more gelatinous future for the North Sea. Limnol Oceanogr 52(1): 480-485.
11. BACC (2006) Assessment of climate change for the Baltic Sea basin. 16 pp.
12. Basilone, G, Guisande, C, Patti, B, Mazzola, S, Cuttitta, A, Bonanno, A, Vergara, AR, Maneiro, I (2006) Effect of habitat conditions on reproduction of the European anchovy (*Engraulis encrasicolus*) in the Strait of Sicily. Fish Oceanogr 15(4): 271-280.
13. Beare, DJ, Batten, S, Edwards, M, Reid, DG (2002) Prevalence of boreal Atlantic, temperate Atlantic and neritic zooplankton in the North Sea between 1958 and 1998 in relation to temperature, salinity, stratification intensity and Atlantic inflow. J Sea Res 48(1): 29-49.
14. Beare, DJ, Burns, F, Greig, A, Jones, EG, Peach, K, Kienzle, M, McKenzie, E, Reid, DG (2004a) Long-term increases in prevalence of North Sea fishes having southern biogeographic affinities. Mar Ecol Prog Ser 284: 269-278.
15. Beare, D, Burns, F, Jones, E, Peach, K, Portilla, E, Greig, T, Mckenzie, E, Reid, D (2004b) An increase in the abundance of anchovies and sardines in the north-western North Sea since 1995. Global Change Biol 10(7) 1209-1213.
16. Beaugrand, G (2004) The North Sea regime shift: evidence, causes, mechanisms and consequences. Prog Oceanogr 60(2-4): 245-262.
17. Beaugrand, G, Reid, PC, Ibanez, F, Lindley, JA, Edwards, M (2002) Reorganization of North Atlantic marine copepod biodiversity and climate. Science 296(5573): 1692-1694.
18. Beaugrand, G, Brander, KM, Lindley, JA, Souissi, S, Reid, PC (2003) Plankton effect on cod recruitment in the North Sea. Nature 426(6967): 661-664.

19. Behrenfeld, MJ, *et al.* (9 co-authors) (2006) Climate-driven trends in contemporary ocean productivuíty. Nature 444: 752-755.

20. Bethoux, JP, Gentili, B, Morin, P, Nicolas, E, Pierre, C, Ruiz-Pino, D (1999) The Mediterranean Sea: a miniature ocean for climatic and environmental studies and a key for the climatic functioning of the North Atlantic. Prog Oceanogr 44(1-3): 131-146.

21. Bethoux, JP, Morin, P, Ruiz-Pino, DP (2002) Temporal trends in nutrient ratios: chemical evidence of Mediterranean ecosystem changes driven by human activity. Deep-Sea Res (II Top Stud Oceanogr) 49(11): 2007-2016.

22. Bigelow, HB (1928) Exploration of the waters of the gulf of Maine. Geogr Rev 18(2): 232-260.

23. Birkeland, C, Dayton, PK (2005) The importance in fishery management of leaving the big ones. Trends Ecol Evol 20(7): 356-358.

24. Björnsson B, Steinarsson A (2002) The food-unlimited growth rate of Atlantic cod (*Gadus morhua*). Can J Fish Aquat Sci 59: 494-502.

25. Bombace, G.B. (2001) Influence of climatic changes on stocks, fish species and marine ecosystems in the Mediterranean Sea. Archo Oceanogr Limnol 22: 67-72.

26. Brander, KM (1994) The location and timing of cod spawning around the British-Isles. ICES J Mar Sci 51(1): 71-89.

27. Brander, KM (1995) The effect of temperature on growth of Atlantic cod (*Gadus morhua* L.). ICES J Mar Sci 52(1): 1-10.

28. Brander, KM (2006) Assessment of possible impacts of climate change on fisheries

29. Brander, KM, Dickson, RR, Edwards, M (2003) Use of Continuous Plankton Recorder information in support of marine management: applications in fisheries, environmental protection, and in the study of ecosystem response to environmental change. Prog Oceanogr 58(2-4): 175-191.

30. Brett, JR (1956) Some principles in the thermal requirements of fishes. Q Rev Biol 31(2): 75-87.

31. Browman, HI, Hutchings, JA, Conover, DO, Stokes, K, Law, R, Walters, C (2000) 'Evolution' of fisheries science. Mar Ecol Prog Ser 208: 301-309.

32. Brown, BR (2003) Neurophysiology - Sensing temperature without ion channels. Nature 421(6922): 495.

33. Bryden, HL, Longworth, HR, Cunningham, SA (2005) Slowing of the Atlantic meridional overturning circulation at 25 degree N. Nature 438(7068): 655-657.

34. Buecher, E (1999) Appearance of *Chelophyes appendiculata* and *Abylopsis tetragona* (Cnidaria, Siphonophora) in the Bay of Villefranche, northwestern Mediterranean. J Sea Res 41(4): 295-307.

35. Burton, DT (1979) Ventilation frequency compensation responses of three eurythermal estuarine fish exposed to moderate temperature increases. J Fish Biol 15(5): 589–600.

36. Caldeira, K, Wickett, ME (2003) Oceanography - Anthropogenic carbon and ocean pH Nature 425(6956): 365.

37. Caldeira, K, Wickett, ME (2005) Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean. J Geophys Res 110(C9): 12 pp.

38. Carotenuto Y, Ianora A, Di Pinto M, Sarno D, Miralto A (2006) Annual cycle of early developmental stage survival and recruitment in the copepods *Temora stylifera* and *Centropages typicus*. Mar Ecol Prog Ser 314: 227–238.

39. Casini, M, Cardinale, M, Hjelm, J (2006) Inter-annual variation in herring, *Clupea harengus*, and sprat, *Sprattus sprattus*, condition in the central Baltic Sea: what gives the tune? Oikos 112(3): 638-650.

40. Cayan, DR (1992) Latent and sensible heat flux anomalies over the northern oceans: Driving the sea surface temperature. J Phys Oceanogr 22(8): 859-881.

41. Ciais *et al.* (32 co-authors) (2005) Europe-wide reduction in primary productivity caused by the heat and drought in 2003: Nature 437: 529-533.

42. Chavez, FP, Ryan, J, Lluch-Cota, SE, Niquen, MC (2003) From anchovies to sardines and back: Multidecadal changes in the Pacific Ocean. Science 299: 217-221.

43. Ciannelli, L, Bailey, KM, Chan, K-S, Belgrano, A, Stenseth, NC (2005) Climate change causing phase transitions of walleye pollock (*Theragra chalcogramma*) recruitment dynamics. Proc R Soc Lond, Ser B: Biol Sci 272(1573): 1735-1743.

44. Clark, RA, Fox, CJ, Viner, D, Livermore, M (2003) North Sea cod and climate change - modelling the effects of temperature on population dynamics. Global Change Biol 9(11): 1669-1680.

45. Clarke, A (1993) Temperature and extinction in the sea: A physiologist's view. Paleobiol 19(4): 499-518.

46. Claussen, M, Ganopolski, A, Brovkin, V, Gerstengarbe, FW, Werner, P (2003) Simulated global-scale response of the climate system to Dansgaard /Oeschger and Heinrich events. Clim Dyn 21(5-6): 361-370.

47. Collie, JS, Richardson, K, Steele, JH (2004) Regime shifts: can ecological theory illuminate the mechanisms? Prog Oceanogr 60(2-4): 281-302.

48. Cook, RM, Sinclair, A, Stefansson, G (1997) Potential collapse of North Sea cod stocks. Nature 385(6616): 521-522.

49. Coutant, CC (1987) Thermal preference: When does an asset become a liability? Environ Biol Fish 18(3): 161-172.

50. Curry, R, Mauritzen, C (2005) Dilution of the Northern North Atlantic Ocean in Recent Decades. Science 308(5729): 1772-1774.

51. Cushing, DH (1984) The gadoid outburst in the North Sea. ICES J Mar Sci 41(2): 159-166.

52. Cushing, DH (1990) Plankton production and year-class strength in fish populations: An update of the match/mismatch hypothesis. Adv Mar Biol 26: 249-294.

53. Davis AJ, Jenkinson, LS, Lawton, JH, Shorrocks, B, Woods, S (1998) Making mistakes when predicting shifts in species in response to global warming. Nature 391: 783-786.

54. Dickson, RR, Brander, KM (1993) Effects of a changing windfield on cod stocks of the North Atlantic. Fish Oceanogr 2(3-4): 124-153.

55. Drinkwater, KF (2005) The response of Atlantic cod (*Gadus morhua*) to future climate change. ICES J Mar Sci 62(7): 1327-1337.

56. Drinkwater, KF (2006) The regime shift of the 1920s and 1930s in the North Atlantic. Prog Oceanogr 68(2-4): 134-151.

57. Dulcic, J, Grbec, B, Lipej, L (1999) Information on the Adriatic ichthyofauna - effect of water warming? Acta Adriat 40(2): 33-43.

58. Dutil, J, Brander, K (2003) Comparing productivity of North Atlantic cod (*Gadus morhua*) stocks and limits to growth production. Fish Oceanogr 12(4-5): 502-512.

59. Ecological Society of America (ESA) (1998) Ecosystem management for sustainable marine fisheries. Ecol Appl 8(Suppl. 1): 174 pp.

60. Edwards, M, Richardson, AJ (2004) Impact of climate change on marine pelagic phenology and trophic mismatch. Nature 430(7002): 881-884.

61. Edwards, M, John, AWG, Johns, DG, Reid, PC (2001) Case history and persistence of the non-indigenous diatom *Coscinodiscus wailesii* in the north-east Atlantic. J Mar Biol Assoc UK 81(2): 207-211.

62. Edwards, M, Beaugrand, G, Reid, PC, Rowden, AA, Jones, MB (2002) Ocean climate anomalies and the ecology of the North Sea. Mar Ecol Prog Ser 239: 1-10.

63. Eisenreich, SJ (2005) Climate Change and the European Water Dimension. European Reports 21553: 253 pp.

64. Engelhard, GH, Heino, M (2004) Dynamics in frequency of skipped reproduction in Norwegian spring-spawning herring. ICES Mar Sci Sympos K:43.

65. Engelhard, GH, Heino, M (2006) Climate change and condition of herring (*Clupea harengus*) explain long-term trends in extent of skipped reproduction. Oecologia 149: 593-603.

66. European Commission (2006) Facts and figures on the CFP. Luxembourg: Office for Official Publications of the European Communities, 37pp.

67. Feely, RA, Sabine, CL, Lee, K, Berelson, W, Kleypas, J, Fabry, VJ, Millero, FJ (2004) Impact of Anthropogenic CO2 on the CaCO3 System in the Oceans. Science 305(5682): 362-366.

68. Ferguson, RG (1958) The prefered temperature of fish and their midsummer distribution in temperate lakes and streams. J Fish Res Bd Canada 15: 607-624.

69. Fernandez J, Saenz J, Zorita E (2003) Analysis of wintertime atmospheric moisture transport and its variability over southern Europe in the NCEP Reanalysis. Climate Research 23: 195-215.

70. Fox, CJ, Planque, BP, Darby, CD (2000) Synchrony in the recruitment time-series of plaice (Pleuronectes platessa L) around the United Kingdom and the influence of sea temperature. J Sea Res 44(1-2): 159-168.

71. Francour, P, Boudouresque, CF, Harmelin, JG, Harmelin-Vivien, ML, Quignard, JP (1994) Are the Mediterranean waters becoming warmer? Information from biological indicators. Mar Pollut Bull 28(9): 523-526.

72. Frank, Kenneth T, Petrie, Brian, Choi, Jae S, Leggett, William C (2005) Trophic Cascades in a Formerly Cod-Dominated Ecosystem. Science 308: 1621-1623.

73. Froese, R, Pauly, D (eds) (2007) FishBase. www.fishbase.org.

74. Fromentin, J-M, Planque, B (1996) Calanus and environment in the eastern North Atlantic. 2. Influence of the North Atlantic Oscillation on *C. finmarchicus* and *C. helgolandicus.* Mar Ecol Prog Ser 134(1-3): 111-118.

75. Fry, FEJ (1947) Effects of the environment on animal activity. Publ Ont Fish Res Lab 68: 1-62.

76. Fry FEJ (1971) The effect of environmental factors on the physiology of fish. Fish Phys 6: 1-98.

77. Garcia, SM, Zerbi, A, Aliaume, C, Do Chi, T, Lasserre, G (2003) The ecosystem approach to fisheries. Issues, terminology, principles, institutional foundations, implementation and outlook. FAO Fish Tech Pap 443, 71 pp.

78. Gaylord, B, Gaines, SD (2000) Temperature or transport? range limits in marine species mediated solely by flow. Am Nat 155(6): 769-789.

79. Genner, MJ, Sims, DW, Wearmouth, VJ, Southall, EJ, Southward, AJ, Henderson, PA, Hawkins, SJ (2004) Regional climatic warming drives long-term community changes of marine fish. Proc R Soc Lond, Ser B: Biol Sci 271(1539): 655-661.

80. Goffart, A, Hecq, J-H, Legendre, L (2002) Changes in the development of the winter-spring phytoplankton bloom in the Bay of Calvi (NW Mediterranean) over the last two decades: a response to changing climate? Mar Ecol Prog Ser 236: 45-60.

81. Gomez F, Gorsky G (2003) Microoplankton cycle in the Northwestern Mediterranean. J Plankton Res 25: 323-329.

82. Gomis, D, Tsimplis, MN, Martin-Miguez, B, Ratsimandresy, AW, Garcia-Lafuente, J, Josey, SA (2006) Mediterranean Sea level and barotropic flow through the Strait of Gibraltar for the period 1958-2001 and reconstructed since 1659. J Geophys Res 111 C11.

83. Goren, M, Galil, BS (2005) A review of changes in the fish assemblages of Levantine inland and marine ecosystems following the introduction of non-native fishes. J Appl Ichthyol 21(4): 364-370.

84. Goy, J, Morand, P, Etienne, M (1989) Long-term fluctuations of *Pelagia noctiluca* (Cnidaria, Scyphomedusa) in the Western Mediterranean Sea. Prediction by climatic variables. Deep-Sea Res I 36(2A): 269-279.

85. Greene, CH, Pershing, AJ (2007) Climate drives sea change. Science 315: 1084-1085.

86. Guisande, C, Vergara, AR, Riveiro, I, Cabanas, JM (2004) Climate change and abundance of the Atlantic-Iberian sardine (*Sardina pilchardus*). Fish Oceanogr 13(2): 91-101.

87. Halsband-Lenk, C, Hirche, HJ (2001) Reproductive cycles of dominant calanoid copepods in the North Sea. Mar Ecol Prog Ser 209: 219-229.

88. Hannesson, R (2007) Geographical distribution of fish catches and temperature variations in the northeast Atlantic since 1945. Mar Pol 31(1): 32-39.

89. Hansen, VK (1960) Investigations on the quantitative and qualitative distribution of zooplankton in the southern part of the Norwegian Sea. Med. Daninarks Fiskeri-og Havundersogelser 2(23): 1-53.

90. Harley, CDG, Randall Hughes, A, Hultgren, KM, Miner, BG, Sorte, CJB, Thornber, CS, Rodriguez, LF, Tomanek, L, Williams, SL (2006) The impacts of climate change in coastal marine systems. Ecol Lett 9(2): 228-241.

91. Harrods, C, Graham, C, Mallela, J (2007) Climate change and the fishes of Britain and Ireland Briefing Paper 4: 1-52.

92. Harvell, CD, Kim, K, Burkholder, JM, Colwell, RR, Epstein, PR, Grimes, DJ, Hofmann, EE, Lipp, EK, Osterhaus, ADME, Overstreet, RM, Porter, JW, Smith, GW, Vasta, GR (1999) Emerging marine diseases-climate links and anthropogenic factors. Science 285: 1505-1510.

93. Harwood, J, Stokes, K (2003) Coping with uncertainty in ecological advice: lessons from fisheries. Trends Ecol Evol 18(12): 617-622.

94. Hauser, L, Adcock, GJ, Smith, PJ, Ramirez, JHB, Carvalho, GR (2002) Loss of microsatellite diversity and low effective population size in an overexploited population of New Zealand snapper (*Pagrus auratus*). Proc Natl Acad Sci USA 99(18): 11742-11747.

95. Hawkins, SJ, Southward, AJ, Genner, MJ (2003) Detection of environmental change in a marine ecosystem - evidence from the western English Channel. Sci Total Environ 310(1-3): 245-256.

96. Hays, GC, Richardson, AJ, Robinson, C (2005) Climate change and marine plankton. Trends Ecol Evol 20(6): 337-344.

97. Hänninen, J, Vuorinen, I, Hjelt, P (2000) Climatic factors in the Atlantic control the oceanographic and ecological changes in the Baltic Sea. Limnol Oceanogr 45(3): 703-710.

98. Helmuth, B, Mieszkowska, N, Moore, P, Hawkins, SJ (2006) Living on the Edge of Two Changing Worlds: Forecasting the Responses of Rocky Intertidal Ecosystems to Climate Change. Annu Rev Ecol, Evol Syst 37: 373-404.

99. Henderson, PA (1998) On the variation in dab Limanda limanda recruitment: a zoogeographic study. J Sea Res 40(1-2): 131-142.

100. Herrick, J, Samuel. F., Norton, JG, Mason, JE, Bessey, C (2007) Management application of an empirical model of sardine-climate regime shifts. Mar Pol 31(1): 71-80.

101. Hjermann, DO, Bogstad, B, Eikeset, AM, Ottersen, G, Gjosaeter, H, Stenseth, NC (2007) Food web dynamics affect Northeast Arctic cod recruitment. Proc R Soc B-Biol Sci 274(1610): 661-669.

102. Hjort, J. (1914) Fluctuations in the great fisheries of Northern Europe - viewed in the light of biological research. Rapp Proc Verb Cons Int Expl Mer 20: 1-288.

103. Hochachka, PW, Somero, GN (2002) Biochemical Adaptation: Mechanism and process in physiological evolution. Oxford University Press, New York.

104. Hoepffner, N *et al.* (2006) Marine and coastal dimension of climate change in Europe. A report to the Europena Water Directors. 1-100.

105. Holbrook, SJ, Schmitt, RJ, Stephens, JSJ (1997) Changes in an assemblage of temperate reef fishes associated with a climate shift. Ecol Appl 7(4): 1299-1310.

106. Houghton, JT, Ding, Y, Griggs, DJ, Noguer, M, van der Linden, PJ, Dai, X, Maskell, K, Johnson, CA (2001) Climate Change 2001: the Scientific Basis. Contributions of Working Group 1 to the third assessment report of the Intergovernmental Panel on Climate Change.

107. Hsieh, C-H, Reiss, CS, Hunter, JR, Beddington, JR, May, RM, Sugihara, G (2006) Fishing elevates variability in the abundance of exploited species. Nature 443(7113): 859-862.

108. Hulme, M, Jenkins, GJ, Xianfu, L, Turpenny, JR, Mitchell, TD, Jones, GR, Lowe, J, Murphy, JM, Hassell, D, Boorman, P, McDonald, R, Hill, S (2002) Climate change scenarios for ther United Kingdom. The UKCIP02 Scientific Report.

109. Hurrell JW (1995) Decadal trends in the North Atlantic Oscillation: regional temperatures and precipitations. Science 269: 676-679.

110. Hurrell, JW, Dickson, RR (2004) Climate variability over the North Atlantic. Marine Ecosystems and Climate Variation: 15-32.

111. Hurrell, JW, Kushnir, Y, Visbeck, M (2001) Perspectives on Climate: The North Atlantic Oscillation. Science 291(5504): 603-605.

112. Hurrell, JW, Visbeck, M, Busalacchi, A, Clarke, RA, Delworth, TL, Dickson, RR, Johns, WE, Koltermann, KP, Kushnir, Y, Marshall, D, Mauritzen, C, McCartney, MS, Piola, A, Reason, C, Reverdin, G, Schott, F, Sutton, R, Wainer, I, Wright, D (2006) Atlantic climate variability and predictability: A CLIVAR perspective. J Clim 19(20): 5100-5121.

113. Hutchings, JA (2000) Collapse and recovery of marine fishes. Nature 406(6798): 882-885.

114. Ianora A, Poulet S, Miralto A (2003) The effect of diatoms on copepod reproduction: a review. Phycologia 42: 351-363.

115. ICES (2006) ICES Working group on Oceanic Hydrography (ICES Cooperative Research Report 280) 53pp.

116. IPCC (2007) Climate Change 2007: The Physical Science Basis: Summary for Policymakers. 1-21.

117. Iversen, SA, Skogen, MD, Svendsen, E (2002) Availability of horse mackerel (*Trachurus trachurus*) in the north-eastern North Sea, predicted by the transport of Atlantic water. Fish Oceanogr 11(4): 245-250.

118. James, A (1988) Are clupeid microphagists herbivorous or omnivorous - a review of the diets of some commercially important clupeids. South Afr J Mar Sci 7: 161-177.

119. Javidpour, J, Sommer, U, Shiganova T (2006) First record of *Mnemiopsis leidyi* A. Agassiz 1865 in the Baltic Sea. Aquat Invas 1(4): 299-302.

120. Jensen, AJ (2003) Atlantic salmon (*Salmo salar*) in the regulated River Alta: Effects of altered water temperature on parr growth. River Res Appl 19(7): 733-747.

121. Jobling, M (1981) Temperature tolerance and the final preferendum - rapid methods for the assessment of optimum growth temperatures. J Fish Biol 19(4): 439-455.

122. Jobling, M (1997) Temperature and growth: Modulation of growth rate via temperature change. In: Global Warming: Implications For Freshwater And Marine Fish: 225-253.

123. Jones, PD, Jonsson, T, Wheeler, D (1997) Extension to the north atlantic oscillation using early instrumental pressure observations from Gibraltar and south-west Iceland. Int J Climatol 17(13): 1433-1450.

124. Jurado-Molina, J, Livingston, P (2002) Climate-forcing effects on trophically linked groundfish populations: implications for fisheries management. Can J Fish Aquat Sci 59(12): 1941-1951.

125. Karl, TR, Trenberth, KE (2003) Modern global climate change. Science 302: 1719-1723.

126. Köster, FW, Hinrichsen, H-H, Schnack, D, St. John, MA, MacKenzie, BR, Tomkiewicz, J, Möllmann, C, Kraus, G, Plikshs, M, Makarchouk, A, Aro, E (2003). Recruitment of Baltic cod and sprat stocks: identification of critical life stages and incorporation of environmental variability into stock-recruitment relationships. Sci Mar 67(Suppl. 1): 129-154.

127. Köster, FW, Möllmann, C, Hinrichsen, H-H, Wieland, K, Tomkiewicz, J, Kraus, G, Voss, R, Markarchouk, A, MacKenzie, BR, St.John, MA, Schnack, D, Rohlf, N, Linkowski, T, Beyer, JE (2005) Baltic cod recruitment - the impact of climate variability on key processes. ICES J Mar Sci 62(7): 1408-1425.

128. Kent, ML, Poppe, TT (1998) Diseases of Seawater Netpen-Reared Salmonid Fishes. Fisheries and Oceans Canada, Nanaimo, Canada 138 pp.

129. Kiehl, JT, Trenberth, KE (1997) Earth's annual global mean energy budget. Bull Am Met Soc 78(2): 197-208.

130. King, DA (2004) Climate change science: adapt, mitigate, or ignore? Science 303(5655): 176-177.

131. Kirby, RR, Johns, DG, Lindley, JA (2006) Fathers in hot water: rising sea temperatures and a Northeastern Atlantic pipefish baby boom. Biol Lett 2(4): 597-600.

132. Kirby, RR, Beaugrand, G, Lindley, JA, Richardson, AJ, Edwards, M, Reid, PC (2007) Climate effects and benthic-pelagic coupling in the North Sea. Mar Ecol Prog Ser 330: 31-38.

133. Klyashtorin, LB (1998) Long-term climate change and main commercial fish production in the Atlantic and Pacific. Fish Res 37(1-3): 115-125.

134. Klyashtorin, LB (2001) Climate change and long-term fluctuations of commercial catches. The possibility of forecasting. FAO Fish Tech Rep.

135. Lehodey, P, Alheit, J, Barange, M, Baumgartner, T, Beaugrand, G, Drinkwater, K, Fromentin, J, Hare, SR, Ottersen, G, Perry, RI, Roy, C, van der Lingen, CD, Werner, F (2006) Climate Variability, Fish, and Fisheries. J Clim 19(20): 5009-5030.

136. Lehtonen, KK (1996) Ecophysiology of the benthic amphipod Monoporeia affinis in an open-sea area of the northern Baltic Sea: Seasonal variations in body composition, with bioenergetic considerations. Mar Ecol Prog Ser 143(1-3): 87-98.

137. Levermann, A, Griesel, A, Hofmann, M, Montoya, M, Rahmstorf, S (2005) Dynamic sea level changes following changes in the thermohaline circulation. Clim Dyn 24(4): 347-354.

138. Levitus, S, Antonov, JI, Boyer, TP, Stephens, C (2000) Warming of the world ocean. Science 287(5461): 2225-2229.Lloret, J, Lleonart, J (2002) Recruitment dynamics of eight fishery species in the northwestern Mediterranean Sea. Sci Mar 66(1): 77-82.

139. Maes, J, Limburg, KE, Van de Putte, A, Ollevier, F (2005) A spatially explicit, individual-based model to assess the role of estuarine nurseries in the early life history of North Sea herring, *Clupea harengus*. Fish Oceanogr 14(1): 17-31.

140. Magnuson, JJ, Crowder, LB, Medvick, PA (1979) Temperature as an ecological resource. Int Comp Biol 19(1): 331-343.

141. Malacic, V, Celio, M, Cermelj, B, Bussani, A, Comici, C (2006) Interannual evolution of seasonal thermohaline properties in the Gulf of Trieste (northern Adriatic) 1991-2003. J Geophys Lett 111 C8.

142. Malzahn, AM, Aberle, N, Clemmesen, C, Boersma, M (2007) Nutrient limitation of primary producers affects fish condition. Limnol. & Oceangr. 52(5): 11pp.

143. Maravelias, CD, Reid, DG (1995) Relationship between herring (*Clupea harengus*, L.) distribution and sea surface salinity and temperature in the northern North Sea. Sci Mar 59(3-4): 327-343.

144. Marteinsdottir, G, Steinarsson, A (1998) Maternal influence on the size and viability of Iceland cod *Gadus morhua* eggs and larvae. J Fish Biol 52(6): 1241-1258.

145. Marty, J-C, Chiaverini, J (2002) Seasonal and interannual variations in phytoplankton production at DYFAMED time-series station, northwestern Mediterranean Sea. Deep-Sea Res (II Top Stud Oceanogr) 49(11): 2017-2030.

146. Mazza, J (1961) Remarques sur la répartition qualitative et quantitative des copépodes en Méditerrannée. Rapp. P. V. Réun. Comm. Int. Explor. Sci. Mer Médit 16: 157-164.

147. Möllmann, C, Kornilovs, G, Sidrevics, L (2000) Long-term dynamics of main mesozooplankton species in the central Baltic Sea. J Plankton Res 22(11): 2015-2038.

148. Möllmann, C, Kornilovs, G, Fetter, M, Köster, F, Hinrichsen, H (2003) The marine copepod, Pseudocalanus elongatus, as a mediator between climate variability and fisheries in the Central Baltic Sea. Fish Oceanogr 12(4-5): 360-368.

149. McCarty, JP (2001) Ecological consequences of recent climate change. Conserv Biol 15(2): 320-331.

150. MCCIP (2006) Marine climate change impacts, annual report card 2006 8pp.

151. McGoodwin, JR (2007) Effects of climatic variability on three fishing economies in high-latitude regions: Implications for fisheries policies. Mar Pol 31(1): 40-55.

152. Medina, A, Abascal, FJ, Megina, C, Garcia, A (2002) Stereological assessment of the reproductive status of female Atlantic northern bluefin tuna during migration to Mediterranean spawning grounds through the Strait of Gibraltar. J Fish Biol 60(1): 203-217.

153. Menard, F, Fromentin, JM (1997) Temporal fluctuations of doliolid abundance in the Bay of Villefranche-sur-Mer (northwestern Mediterranean Sea) from 1967 to 1990. Oceanol Acta 20(5): 733-742.

154. Menard, F, Dallot, S, Thomas, G, Braconnot, JC (1994) Temporal fluctuations of two Mediterranean salp populations from 1967 to 1990. Analysis of the influence of environmental variables using a Markov chain model. Mar Ecol Prog Ser 104(1-2): 139-152.

155. Miller, KA (2007) Climate variability and tropical tuna: Management challenges for highly migratory fish stocks. Mar Pol 31(1): 56-70.

156. Miller, KA, Munro GR (2004) Climate and Cooperation: A New Perspective on the Management of Shared Fish Stocks. Mar Res Econ 19(3): 367-393.

157. Mills, CA, Mann RHK (1985) Environmentally induced fluctuations in year -class strength and their implications for management. J Fish Biol 27(Suppl. A): 209-226.

158. Misund, OA, Vilhjalmsson, H, Jakupsstovu, SH, Rottingen, I, Belikov, S, Asthorsson, O, Blindheim, J, Jonsson, J, Krysov, A, Malmberg, SA, Sveinbjornsson, S (1998) Distribution, migration and abundance of Norwegian spring spawning herring in relation to the temperature and zooplankton biomass in the Norwegian Sea as recorded by coordinated surveys in Spring and Summer 1996. Sarsia 83(2): 117-127.

159. Molinero, JC, Ibanez, F, Nival, P, Buecher, E, Souissi, S (2005a) North Atlantic climate and northwestern Mediterranean plankton variability. Limnol Oceanogr 50(4): 1213-1220.

160. Molinero, JC, Ibanez, F, Souissi, S, Chifflet, M, Nival, P (2005b) Phenological changes in the Northwestern Mediterranean copepods *Centropages typicus* and *Temora stylifera* linked to climate forcing. Oecologia 145(4): 640-649.

161. Moore, MV, Pace, ML, Mather, JR, Murdoch, PS, Howarth, RW, Folt, CL, Chen, CY, Hemond, HF, Flebbe, PA, Driscoll, CT (1997) Potential effects of climate change on freshwater ecosystems of the New England/Mid-Atlantic region. In: Special Issue: Freshwater Ecosystems And Climate Change: 925-947.

162. Muus, BJ, Nielsen JG (1999) Die Meeresfische Europas in Nordsee, Ostsee und Atlantik. Kosmos Verlag 336 pp.

163. Naylor, RL, Goldburg, RJ, Primavera, JH, Kautsky, N, Beveridge, MCM, Clay, J, Folke, C, Lubchenco, J, Mooney, H, Troell, M (2000) Effect of aquaculture on world fish supplies Nature 405(6790): 1017-1024.

164. Nehring, Stefan (2003) Alien species in the North Sea: invasion success and climate warming. Ocean Chall 13(3): 12-16.

165. O'Brien, CM, Fox, CJ, Planque, B, Casey, J (2000) Climate variability and North Sea cod Nature 404(6774): 142.

166. Olsen, EM, Heino, M, Lilly, GR, Morgan, MJ, Brattey, J, Ernande, B, Dieckmann, U (2004) Maturation trends indicative of rapid evolution preceded the collapse of northern cod. Nature 428(6986): 932-935.

167. Orr JC *et al.* (26 co-authors) (2005) Anthropogenic ocean acidification over the twenty-first century and its impacts on calcifying organisms. Nature 437: 681-686.

168. Ottersen, G, Planque, B, Belgrano, A, Post, E, Reid, PC, Stenseth, NC (2001) Ecological effects of the North Atlantic Oscillation. Oecologia 128(1): 1-14.

169. Parmesan, C (2006) Ecological and evolutionary responses to recent climate change Annu Rev Ecol Evol Syst 37: 637-669.

170. Parmesan, C, Gaines, S, Gonzalez, L, Kaufman, DM, Kingsolver, J, Townsend Peterson, A, Sagarin, R (2005) Empirical perspectives on species borders: from traditional biogeography to global change. Oikos 108(1): 58-75.

171. Parmesan, C, Yohe, G (2003) A globally coherent fingerprint of climate change impacts across natural systems. Nature 421(6918): 37-42.

172. Parsons, LS, Lear, WH (2001) Climate variability and marine ecosystem impacts: a North Atlantic perspective. Prog Oceanogr 49(1-4): 167-188.

173. Patz, JA, Campbell-Lendrum, D, Holloway, T, Foley, JA (2005) Impact of regional climate change on human health. Nature 438: 310-317.

174. Pauly, D, Watson, R, Alder, J (2005) Global trends in world fisheries: impacts on marine ecosystems and food security. Phil Trans R Soc B 360: 5-12.

175. Pawlak, JF *et al.* (2007) Climate change in the Baltic Sea area. Draft HELCOM thematic assessment in 2007, 53 pp.

176. Pörtner, HO (2002) Physiological basis of temperature-dependent biogeography: trade-offs in muscle design and performance in polar ectotherms. J Exp Biol 205(15): 2217-2230.

177. Pörtner H O, Knust R (2007) Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science 315: 95-97.

178. Pörtner, HO, Mark, FC, Bock, C (2004) Oxygen limited thermal tolerance in fish? Answers obtained by nuclear magnetic resonance techniques. Respir Physiol Neuro 141(3): 243-260.

179. Pörtner, HO, Langenbuch, M, Michaelidis, B (2005) Synergistic effects of temperature extremes, hypoxia, and increases in CO2 on marine animals: From Earth history to global change. J Geophys Res 110 C9.

180. Pearson RG & Dawson TP (2003) Predicting the impacts of climate change on the distribution of species: are bioclimate envelope models useful? Glob Ecol Biogeogr 12: 361-371.

181. Perry, AL, Low, PJ, Ellis, JR, Reynolds, JD (2005) Climate Change and Distribution Shifts in Marine Fishes. Science 308(5730): 1912-1915.

182. Persson, L (1986) Temperature-induced shift in foraging ability in two fish species, roach (*Rutilus rutilus*) and perch (*Perca fluviatilis*) - implications for coexistence between poikilotherms. J Anim Ecol 55(3): 829-839.

183. Peterson, BJ, McClelland, J, Curry, R, Holmes, RH, Walsh, JE, Aagaard, K (2006) Trajectory shifts in the Arctic and Subarctic freshwater cycle. Science 313: 1061-1066.

184. Planque, B, Fox, CJ (1998) Interannual variability in temperature and the recruitment of Irish Sea cod. Mar Ecol Prog Ser 172: 101-105.

185. Planque, B, Fredou, T (1999) Temperature and the recruitment of Atlantic cod (*Gadus morhua*). Can J Fish Aquat Sci 56(11): 2069-2077.

186. Poloczanska, ES, Cook, RM, Ruxton, GD, Wright, PJ (2004) Fishing vs. natural recruitment variation in sandeels as a cause of seabird breeding failure at Shetland: a modelling approach. ICES J Mar Sci 61(5): 788-797.

187. Polovina, JJ (2005) Climate Variation, Regime Shifts, and Implications for Sustainable Fisheries. Bull Mar Sci 76(2): 233-244.

188. Pope, JG, Symes, D (2000) An ecosystem based approach to the Common Fisheries Policy: defining the goals. Eng Nat: 40 pp.

189. Rahmstorf, S (2000) The thermohaline ocean circulation: a system with dangerous thresholds? Clim Change 46(3): 247-256.

190. Rahmstorf, S (2002) Ocean circulation and climate during the past 120,000 years. Nature 419(6903): 207-214.

191. Raper, SCB: Viner, D, Hulme, M, Barrow, EM (1997) Global warming and the British Isles 454pp.

192. Ravier, C, Fromentin, J (2004) Are the long-term fluctuations in Atlantic bluefin tuna (*Thunnus thynnus*) population related to environmental changes? Fish Oceanogr 13(3): 145-160.

193. Riebesell, U, Zondervan, I, Rost, B, Tortell, PD, Zeebe, RE, Morel, FMM (2000) Reduced calcification of marine plankton response to increased atmospheric CO_2. Nature 407: 364-367.

194. Regier, H, Holmes, J, Pauly, D (1990) Influence of temperature-changes on aquatic ecosystems - an interpretation of empirical-data. Trans Am Fish Soc 119(2): 374-389.

195. Renz, J, Hirche, H-J (2005) Life cycle of *Pseudocalanus acuspes* Giesbrecht (Copepoda, Calanoida) in the Central Baltic Sea: I. Seasonal and spatial distribution. Mar Biol 148(3): 567 – 580.

196. Reynolds, W, Casterlin, M (1977) Temperature preferences of four fish species in an electronic thermoregulatory shuttlebox. Prog Fish Cult 39(3): 123-125.

197. Rixen M, Beckers JM, Levitus S, Antonov J, Boyer T, Maillard C, Fichaut M, Balopoulos E, Iona S, Dooley H, Garcia MJ, Manca B, Giogetti A, Manzella G, Mikhailov N, Pinardi N, Zavatarelli M (2005) The Western Mediterranean deep water: aproxy for climate change. Geophys Res Lett 32.

198. Rodwell, MJ, Rowell, DP, Folland, CK (1999) Oceanic forcing of the wintertime North Atlantic Oscillation and European climate. Nature 398(6725): 320-323.

199. Rogers, J (1984) The association between the North-Atlantic Oscillation and the Southern Oscillation in the Northern hemisphere. Month Weath Rev 112(10): 1999-2015.

200. Root, TL, Price, JT, Hall, KR, Schneider, SH, Rosenzweig, C, Pounds, JA (2003) Fingerprints of global warming on wild animals and plants. Nature 421(6918): 57-60.

201. Rose, GA (2005) On distributional responses of North Atlantic fish to climate change. ICES J Mar Sci 62(7): 1360-1374.

202. Ruddiman, WF, Thomson, JS (2001) The case for human causes of increased atmospheric CH_4. Quat Sci Rev 20(18): 1769-1777.

203. Sabine, CL, Feely, RA, Gruber, N, Key, RM, Lee, K, Bullister, JL, Wanninkhof, R, Wong, CS, Wallace, DWR, Tilbrook, B, Millero, FJ, Peng, T-H, Kozyr, A, Ono, T, Rios, AF (2004) The oceanic sink for anthropogenic CO_2. Science 305(5682): 367-371.

204. Sarmiento, JL, Slater, R, Barber, R, Bopp, L, Doney, SC, Hirst, AC, Kleypas, J, Matear, R, Mikolajewicz, U, Monfray, P, Soldatov, V, Spall, SA, Stouffer, R (2004) Response of ocean ecosystems to climate warming. Global Biogeochem Cycles 18(3)

205. Scavia, D, Field, JC, Boesch, DF, Buddemeier, RW, Burkett, V, Cayan, DR, Fogarty, M, Harwell, MA, Howarth, RW, Mason, C, Reed, DJ, Royer, TC, Sallenger, AH, Titus, JG (2002) Climate Change Impacts on U.S. Coastal and Marine Ecosystems Estuaries. 25(2): 149-164.

206. Schär, C, Vidale, PL, Lüthi, D, Frei, C, Häberli, C, Liniger, MA, Appenzeller, C (2004) The role of increasing temperature variability in European summer heatwaves. Nature 427, 332-336.

207. Schrank, WE (2007) The ACIA, climate change and fisheries. Mar Pol 31(1): 5-18.

208. Send, U, Font, J, Krahmann, G, Millot, C, Rhein, M, Tintore, J (1999) Recent advances in observing the physical oceanography of the western Mediterranean Sea. Prog Oceanogr 44(1-3): 37-64.

209. Sharp, GD (2003) Future climate change and regional fisheries: a collaborative analysis. FAO Fish Tech Pap 452 75p.

210. Sheppard, C (2004) Sea surface temperature 1871-2099 in 14 cells around the United Kingdom. Mar Pollut Bull 49(1-2): 12-16.

211. Siegenthaler, U, Monnin, E, Kawamura, K, Spahni, R, Schwander, J, Stauffer, B, Stocker, TF, Barnola, JM, Fischer, H (2005) Supporting evidence from the EPICA Dronning Maud Land ice core for atmospheric CO_2 changes during the past millennium. Tellus Ser B-

Chem Phys Meteorol: 57(1): 51-57.

212. Sims, DW, Wearmouth, VJ, Southall, EJ, Hill, JM, Moore, P, Rawlinson, K, Hutchinson, N, Budd, GC, Righton, D, Metcalfe, J, Nash, JP, Morritt, D (2006) Hunt warm, rest cool: bioenergetic strategy underlying diel vertical migration of a benthic shark. J Anim Ecol 75(1): 176-190.

213. Sirabella, P, Giuliani, A, Colosimo, A, Dippner, JW (2001) Breaking down the climate effects on cod recruitment by principal component analysis and canonical correlation. Mar Ecol Prog Ser 216: 213-222.

214. Sissener, EH, Bjoerndal, T (2005) Climate change and the migratory pattern for Norwegian spring-spawning herring, implications for management. Mar Policy 29(4): 299-309.

215. Smetacek V, Nicol, S (2005)Polar ocean ecosystems in a changing world. Nature 437: 362-368.

216. Somarakis, S, Ganias, K, Siapatis, A, Koutsikopoulos, C, Machias, A, Papaconstantinou, C (2006) Spawning habitat and daily egg production of sardine (*Sardina pilchardus*) in the eastern Mediterranean. Fish Oceanogr 15(4): 281-292.

217. Southward, A, Boalch, G, Maddock, L (1988) Fluctuations in the herring and pilchard fisheries of devon and cornwall linked to change in climate since the 16th-Century. J Mar Biol Assoc UK 68(3): 423-445.

218. Southward, A, Hawkins, S, Burrows, M (1995) 70 years observations of changes in distribution and abundance of zooplankton and intertidal organisms in the Western English-Channel in relation to rising sea temperature. J Therm Biol 20(1-2): 127-155.

219. Spahni, R, Chappellaz, J, Stocker, TF, Loulergue, L, Hausammann, G, Kawamura, K, Fluckiger, J, Schwander, J, Raynaud, D, Masson-Delmotte, V, Jouzel, J (2005) Atmospheric methane and nitrous oxide of the late Pleistocene from Antarctic ice cores. Science 310(5752): 1317-1321.

220. Steele, JH (2004) Regime shifts in the ocean: reconciling observations and theory. Prog Oceanogr 60(2-4): 135-141.

221. Stenevik, EK, Sundby, S (2007) Impacts of climate change on commercial fish stocks in Norwegian waters. Mar Pol 31(1): 19-31.

222. Stenseth, NC, Mysterud, A, Ottersen, G, Hurrell, JW, Chan, K-S, Lima, M (2002) Ecological Effects of Climate Fluctuations. Science 297(5585): 1292-1296.

223. Stenseth, NC, Ottersen, G, Hurrell, JW, Mysterud, A, Lima, M, Chan, K-S, Yoccoz, NG, Aadlandsvik, B (2003) Review article. Studying climate effects on ecology through the use of climate indices: the North Atlantic Oscillation, El Nino Southern Oscillation and beyond. Proc R Soc Lond, Ser B: Biol Sci 270(1529): 2087-2096.

224. Stott, PA, Stone, DA, Allen, MR (2004) Human contributions to the heatwave of 2003. Nature 432: 610-614.

225. The Royal Society (2005) Ocean acidification due to increasing atmospheric carbon dioxide 12/05 68 pp.

226. Theocharis, A, Nittis, K, Kontoyiannis, H, Papageorgiou, E, Balopoulos, E (1999) Climatic changes in the Aegean Sea influence the Eastern Mediterranean thermohaline circulation (1986-1997). Geophys Res Lett 26(11): 1617-1620.

227. Tietenberg, T (2003) The tradable-permits approach to protecting the commons: Lessons for climate change. Oxf Rev Econ Policy 19(3): 400-419.

228. Tonn, WM (1990) Climate change and fish communities: A conceptual framework. Trans Am Fish Soc.

229. Trigo I, Davies T, Bigg, G. (2000) Decline in Mediterranean rainfall caused by weakening of Mediterranean cyclones. Geophys Res Lett 27: 2913-2916.

230. Tsimplis M, Josey SA (2001) Forcing on the Mediterranean Sea by atmospheric oscillations over the North Atlantic. Geophys Res Lett 28: 803-806.

231. Tsimplis, MN, Alvarez-Fanjul, E, Gomis, D, Fenoglio-Marc, L, Perez, B (2005) Mediterranean Sea level trends: Atmospheric pressure and wind contribution. Geophy Res Lett 32(20): 1-4.

232. Turrell, W, Henderson, E, Slesser, G, Payne, R, Adams, R (1992) Seasonal-Changes In The Circulation Of The Northern North-Sea. Cont Shelf Res 12(2-3): 257-286.

233. Veizer, J (2005) Celestial climate driver: A perspective from four billion years of the carbon cycle. Geosci Can 32(1): 13-28.

234. Vignudelli S, Gasparini G, Astraldi M, Schiano ME (1999) A possible influence of the North Atlantic Oscillation on the circulation of the Western Mediterranean Sea. Geophys Res Lett 26: 623-626.

235. Vilhjalmsson, H (1997) Climatic variations and some examples of their effects on the marine ecology of Icelandic and Greenland waters, in particular during the present century. Rit Fisk J Mar Res Inst 15(1): 7-29.

236. Visbeck, MH, Hurrell, JW, Polvani, L, Cullen, HM (2001) The North Atlantic Oscillation: Past, present, and future. Proc Nat Am Soc 98(23): 12876-12877.

237. Vitousek, P (1994) Beyond global warming - ecology and global change. Ecology 75(7): 1861-1876.

238. Walther, G-R, Post, E, Convey, P, Menzel, A, Parmesan, C, Beebee, TJC, Fromentin, J-M, Hoegh-Guldberg, O, Bairlein, F (2002) Ecological responses to recent climate change. Nature 416(6879): 389-395.

239. Walther, GR, Hughes, L, Vitousek, P, Stenseth, NC (2005) Consensus on climate change. Trends Ecol Evol 20(12): 648-649.

240. Wang, T, Overgaard, J (2007) The heartbreak of adapting to global warming. Science 315(5808): 49-50.

241. Weiss RF (1970) The solubility of nitrogen, oxygen and argon in water and seawater. Deep-Sea Res 17: 721-735.

242. WBGU Report (2006) The future Oceans- Warming up, rising high, turning sour. 110pp.

243. Whitehead, PJP, Nelson, GJ, Wongratana, T (1988) FAO species catalogue. Vol. 7. Clupeoid fishes of the world (Suborder Clupeoidei). An annotated and illustrated catalogue of the herrings, sardines, pilchards, sprats, shads, anchovies and wolf-herrings. Part 2 – Engraulididae. FAO fish synop 125(7/2): 305-579.

244. Wieland, K, Waller, U, Schnack, D (1994) Development of Baltic cod eggs at different levels of temperature and oxygen content. Dana 10: 163-177.

245. Wiltshire KH, Manly BFJ (2004) The warming trneds at Helgoland Roads, North Sea: Phytoplankton response. Helgol Mar Res 58: 269-273.

246. Winder, M, Schindler, DE (2004) Climate change uncouples trophic interactions in an aquatic system. Ecology 85(11): 3178-3178.

247. Wonham, MJ, Carlton, JT, Ruiz, GM, Smith, LD (2000) Fish and ships: Relating dispersal frequency to success in biological invasions. Mar Biol 136(6): 1111-1121.

248. Worm, B, Myers, RA (2003) Meta-analysis of cod-shrimp interactions reveals top-down control in oceanic food webs. Ecology 84(1): 162-173.

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