RECLAIM

REsolving CLimAtic IMpacts on fish stocks

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Final Activity Report
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Thematic Priority 8.1 Modernisation and sustainability of fisheries, including aquaculture-based production systems

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Project coordinator organisation: IMARES

Executive summary

The EU FP6 project RECLAIM (Resolving CLimAtic IMpacts on fish stocks) studied the impact of climate change on the productivity and distribution of fish and shellfish populations. RECLAIM reviewed the strengths and weaknesses of current scientific knowledge with the aim to detect critical knowledge-gaps and to provide sound advice, recommendations and working hypotheses for future research. The study focussed on the northeast Atlantic, from the Barents Sea in the north to the Bay of Biscay in the south, including the Baltic Sea. It comprised a structured literature review, investigations on the present usefulness of regional downscaling, application of new methodologies to link biology to climate changes, and specific case studies for several fish species.

Ocean climate shows decadal and multi-decadal oscillations that have major effects on the ecosystem and fish. Global Circulation Models (GCM) consistently predict an increase in air and sea temperature, changes in precipitation and loss of sea ice cover. Effects on wind and storms are less certain. There is a large body of scientific evidence showing that changes in fish populations (recruitment variation, growth, distribution, phenology, etc) are correlated to variations in ocean climate such as the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO). The mechanisms behind these changes are largely unknown. A problem in the study of future climate change impacts on marine ecosystems is that the present GCMs, which are the key tools to model global changes in meteorology and oceanography, are limited in their capacity to hindcast the observed variations in ocean climate at the regional scales in the northeast Atlantic, and hence increases the uncertainty in future climate projections. This is in part related to too coarse horizontal resolution to adequately capture several of the important dynamical features at the regional scales.

There is, however, ample evidence that climate change will affect the primary and secondary productivity of marine ecosystems, although the impacts will differ across geographic regions. Marine primary production is strongly affected by solar radiation, upwelling as well as by the development and breakdown of stratification. Given the problems with the GCMs and application of downscaling to the regional scale, RECLAIM used a number of coupled bio-physical models have been used to explore the possible impact of climate-driven changes in temperature, radiation and winds, known as “what-if” scenarios. Model projections for the North Sea, Baltic and Bay of Biscay indicated in these regions that: (i) changes in phytoplankton production are most strongly affected by changes in solar radiation, with smaller effects caused by changes in wind speed and the weakest effects caused by changes in air temperature; (ii) the combined effect of an increase in solar radiation, wind speed and air temperature was associated with the largest potential for increased primary productivity; (iii) the sensitivity of lower trophic level production to changes in river nutrient loads is restricted to the coastal waters (particularly in the southern North Sea and at the mouths of major rivers) with little impacts in the wider North Sea, while in the Bay of Biscay, such changes produce a negative response similar to that due to changes in air temperature; (iv) secondary production and zooplankton biomass appear to be more sensitive to changes in climate forcing compared to primary production.

To provide a basis for the mechanistic understanding of how climate change may impact fish and shellfish populations, a framework was developed based on first principles of physiology and ecology. Fish and shellfish have complex life histories

comprising a series of life stages (eggs, larvae, juveniles and adults) each with specific habitat requirements. A prerequisite for a population to survive is life cycle closure. Climate change may impact this through effects on particular life stages or the connectivity between habitats. On the level of the ecosystem, climate change may impact fish populations through direct effects on their physiology such as metabolism or indirectly through changes in the distribution and abundance of their food or predators (including jellyfish).

Knowledge on the eco-physiology of the various life history stages provides a solid foundation to evaluate the likely, general impacts of climate change on fish and may provide specific insight into the relative sensitivity of different life stages. There is some evidence that life stages differ in their sensitivity to environmental factors such as temperature. In terms of identifying critical periods, there was no common pattern among species with respect to changes in thermal tolerance among eggs, larvae, juveniles and adults although the adult spawners and early life stages often exhibit the most narrow range in tolerable temperatures. However, prey availability, particularly during the late larval and early juvenile periods, appears to be one of the most important environmental factors creating density-dependent fluctuations in populations in both the northwest Pacific and northeast Atlantic. There is a lack of basic information on temperature tolerance and sensitivity for many species, on the impacts of “multiple stressors” (e.g., the interaction between temperature and other key factors such as salinity and/or dissolved O_2) and on the impact of ocean acidification. Finally, the adaptive capacity of fish (and other organisms) to ongoing changes in temperature and other abiotic factors is largely unknown. Very little work has been carried out on fish ecophysiology since the 1970s and yet such information is becoming increasingly useful as researchers attempt to predict the future implications of climate change.

It is uncontested that simulation models that couple the physics of the ocean and the biology and ecological interactions among species are an indispensable tool in the study of climate change. Bio-physical model studies suggested that continued warming will make vast areas of the North Sea unsuitable for species such as cod (winter-spring spawners) but will have little impact on species such as sprat (spring-summer spawners). On the other hand, cod productivity should increase in the Barents Sea where the disappearance of sea ice will result in increased primary production. Another study in RECLAIM in the Kattegat suggested that the response to increasing temperatures was stronger for zooplankton than for phytoplankton causing higher grazing impact on phytoplankton, faster recycling of nutrients and less sedimentation of organic matter to the sea floor. Climate warming is therefore expected to be more detrimental for benthic animals than for pelagic species (with possible consequences for fish that feed on benthic prey types).

Climate change is expected to have substantial implications for fisheries. Further research is needed in this area, such as: (i) modelling of how fishers will respond to changes in fish distribution, including impacts on distance that fishers will need to travel to maintain catches (additional fuel costs, days at sea etc.), the potential impact on stocks that span national boundaries and consequences for quota allocation, the potential impact on marine-protected-area effectiveness if protected species move outside the boundaries of the closed area; (ii) the potential impact of climate change on fish ‘catchability’, e.g. whether fish behave differently in warmer waters (whether they respond differently to an incoming trawl), whether the geometry of fishing gears will change as species and fisheries move into deeper waters, and the potential impact of ocean acidification on noise-transmission in the ocean, which could impact on the ability of fish to detect incoming trawls; and (iii) the socio-economic implications of changed fisheries yields associated with climate change, yields are predicted to increase in the north but decrease in the south of Europe) and possible mitigation methods for fisheries and fishery policy makers.

Based on the results of RECLAIM, working hypothesis for future research as well as recommendations for the future research agenda were made. Recommendations centred around the need for (i) improving global circulation models to capture decadal variations in ocean climate; (ii) regional downscaling of global circulation models; (iii) the development and extension of regional ecosystem models to capture both the life cycle closure and the pelagic – benthic coupling; (iv) experimental work on the eco-physiology of key species and life stages; (v) the need for maintaining (plankton, fish) and extending (benthos) long-term monitoring of ecosystem components and (vi) further study to understand the impacts of climate change on fisheries.

RECLAIM (Resolving CLimAtic IMpacts on fish stocks)

The EU FP6 project RECLAIM (Resolving CLimAtic IMpacts on fish stocks) studied the impact of climate change on the productivity and distribution of fish and shellfish populations. RECLAIM reviewed the strengths and weaknesses of current scientific knowledge with the aim to detect critical knowledge-gaps and to provide sound advice, recommendations and working hypotheses for future research. The study focussed on the northeast Atlantic and comprised of a structured literature review, investigations on the present usefulness of regional downscaling, application of new methodologies to link biology to climate changes, and specific case studies for several fish species. Nine institutes, mainly from northwest European states collaborated closely in the project (Table 1). To provide a basis for the mechanistic understanding of how climate change may impact fish and shellfish populations, a framework was developed that was based on first principles of physiology and ecology. The framework allowed us to structure the literature review on ocean climate, marine ecosystems and fish populations, select the environmental variables and oceanographic features that are relevant to fish and likely to be affected by climate change, and derive working hypotheses based on the mechanisms determining the response of fish to climate change. In a second step, patterns of change were explored by analysing biological time-series in relation to climatic variables. Specific mechanisms for change were examined using biophysical models, to increase our understanding of the processes involved. Finally, the implications of future climate on ecosystem processes and the dynamics of fish populations were explored. Achievements, working hypotheses and recommendations for future research are summarised below.

Table 1 List of contractors and subcontractors

IMARES	Institute for Marine Resources and Ecosystem Studies	Netherlands
FRS	Fisheries Research Services	UK
Cefas	Centre for Environment, Fisheries & Aquaculture Science	UK
IFREmer	Institut Français de Recherche pour l’Exploitation de la mer	France
UniH	Institute of Hydrobiology and Fishery Science, University of Hamburg	Germany
DTU-Aqua	National Institute of Aquatic Resources, Technical University of Denmark	Denmark
IMR	Institute of Marine Research	Norway
NIOZ	Royal Netherlands Institute for Sea Research	Netherlands
UiB-GFI	University of Bergen, Geophysical Institute	Norway
[1]DMI	Danish Meteorological Institute	Denmark
[1]NERI	National Environmental Research Institute	Denmark

[1]Subciontractors to DTU-Aqua.

Ocean climate

Our expectations of how increased concentrations of green house gasses will affect our climate rely on the outputs of Global Circulation Models (GCMs). GCMs consistently predict an increase in both air and sea temperature (larger changes in northern areas), changes in precipitation (increase in northern Europe and a decrease in southern Europe) and a decrease in the sea ice. With higher salinity in the tropics due to higher evaporation, some of the water will be transported northward and this will lead to increased salinity in several sea areas in the northeast Atlantic, including the Barents Sea. In the Baltic, salinities will decrease because of increased precipitation. The Meridional Overturning Circulation (MOC) is expected to weaken by approximately 25% by 2100 but the waters in the northeastern Atlantic are expected to continue to warm in spite of reduced MOC. The predictions about changes in wind fields and upwelling processes are more variable and in some cases models offer conflicting and diametrically opposite predictions for the future. The increase in CO_2 concentrations in the atmosphere will result in increased CO_2 concentrations in the ocean and a reduction in the pH. RECLAIM did not specifically address the problem of ocean, as it was beyond the scope of the project.. Nevertheless, increased acidification is expected to have significant effects on marine ecological processes and may affect fish in unexpected (and indirect) ways such as neurological changes impacting odour recognition, leading to problems in natal homing and hence changes in connectivity of life stages to essential habitats, and changes in the fertilisation of eggs and the development of early fish larvae. Also, it will occur concurrently with climate change, the combined effect of which is not clear.

There is a large body of scientific evidence showing that changes in fish populations (recruitment variation, growth, distribution) are correlated to variations in ocean climate, such as the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO). One problem in the study of climate change impacts on marine ecosystems is that the Global Circulation Models, which are the key tools to model the changes in meteorology and oceanography, are not capable of hindcasting the observed patterns in the NAO and the AMO. Finer horizontal and vertical resolution in the GCMs should be explored. For development of future climate scenarios, initialization of the ocean and atmosphere to present day conditions is needed. This is especially important for projections of the near future, e.g. the next 10-20 years. A concerted research effort towards improving the GCMs, including resolving these two major modes, is required.

Further research is required to develop downscaling strategies for dynamic regional shelf sea models. Such models are critical for improving and providing quantitative estimates of the impacts of climate change on the regional biology. This research needs to include careful assessment of the underlying GCMs used for downscaling to regional models in terms of the GCMs ability to reproduce past and present climate. Most downscaling efforts to date have used only one GCM but these studies have revealed that downscaling should be carried out using several GCMS to avoid model-specific problems. Until this is done, the downscaling will not provide realistic future projections for regional impact studies. Downscaling strategies need to include both atmospheric forcing and open ocean boundary condition issues, and coupling of the atmosphere and ocean at both global and regional scales.

Research is also needed to address uncertainty in regional projections arising from both the regional physical and ecosystem models, as well as global projections. Also, simple ways to express these uncertainties are needed for those using the results of the models.

Marine ecosystem

Marine ecosystems are considered to be primarily regulated by bottom-up processes (i.e. climate, influencing phytoplankton productivity which in-turn influences 'higher' trophic levels). Only coldwater ecosystems characterised by relatively few species are thought to be regulated primarily by top-down processes (top predators and fishing). Top-down regulated ecosystems will be more sensitive to fishing effects. A first exploration of the relative roles of fishing and changes in primary production using a suite of ecosystem and food-web models in a number of different ecosystems including the North Sea, Irish Sea and western Mediterranean suggested that fishing was found to be the primary forcing factor in the North Sea, however primary production was found to be more important in the Irish Sea.

There is ample evidence that climate change will affect the primary and secondary productivity of ecosystems in the future, although the impacts will differ across geographic regions. Primary production will likely increase in the Barents Sea, because of increased light levels through the disappearance of sea ice and higher nutrient levels from the expected increased influence of Atlantic Water inflow. In more southerly regions, such as the Bay of Biscay, increased stratification caused by warming will likely reduce overall primary production. There will also be changes in plankton distribution and community structure. For example with the decreased salinities in the Baltic Sea, there will be an increase in neritic species and they will extend their distribution farther seaward. In other European waters, many species are expected to expand their distribution northward in the future, although the rate of movement will not necessarily be the same for all species and hence this could potentially change community structure as well as ecosystem functioning.

Marine primary production is strongly affected by solar radiation, upwelling as well as by the development and breakdown of stratification. A number of coupled bio-physical models have been used to explore "what-if" scenarios for the North Sea and Bay of Biscay, in particular the possible impact of climate-driven changes in temperature, short wave radiation and winds (Figure 1). Despite numerous differences in formulations and parameterisation employed in the different models, surprisingly coherent results were produced. Model projections indicated that: (i) changes in phytoplankton production are most strongly affected by changes in solar radiation, with smaller effects caused by changes in wind speed and the weakest effects caused by changes in air temperature; (ii) the combined effect of an increase in solar radiation, wind speed and air temperature had the largest potential for increased primary productivity; (iii) the sensitivity of lower trophic level production to changes in river nutrient loads is restricted to coastal waters (particularly in the southern North Sea and at the mouths of major rivers) with little impacts in the wider North Sea, while in the Bay of Biscay, such changes produce a negative response similar to that due to changes in air temperature; (iv) secondary production and zooplankton biomass appear to be more sensitive to changes in climate forcing compared to primary production. Application of a 1-D model in the Kattegat suggested that (v) primary production increase due to higher remineralisation rates in the spring bloom will be lower due to higher grazing pressure and increased pelagic heterotrophy; (vi) sedimentation of organic matter will likely decrease resulting in a reduction of benthic productivity. Benthic filter feeders will be less affected while deposit feeders and subsurface feeders (within the sediment) are predicted to suffer the largest declines in biomass and this may have consequences for fish species that prey upon benthic resources.

Long-term monitoring programs of various ecosystem components are an essential basis for the study of climate change impacts on marine ecosystems. There is a clear gap in monitoring data and process understanding, especially with regard to the benthos component.

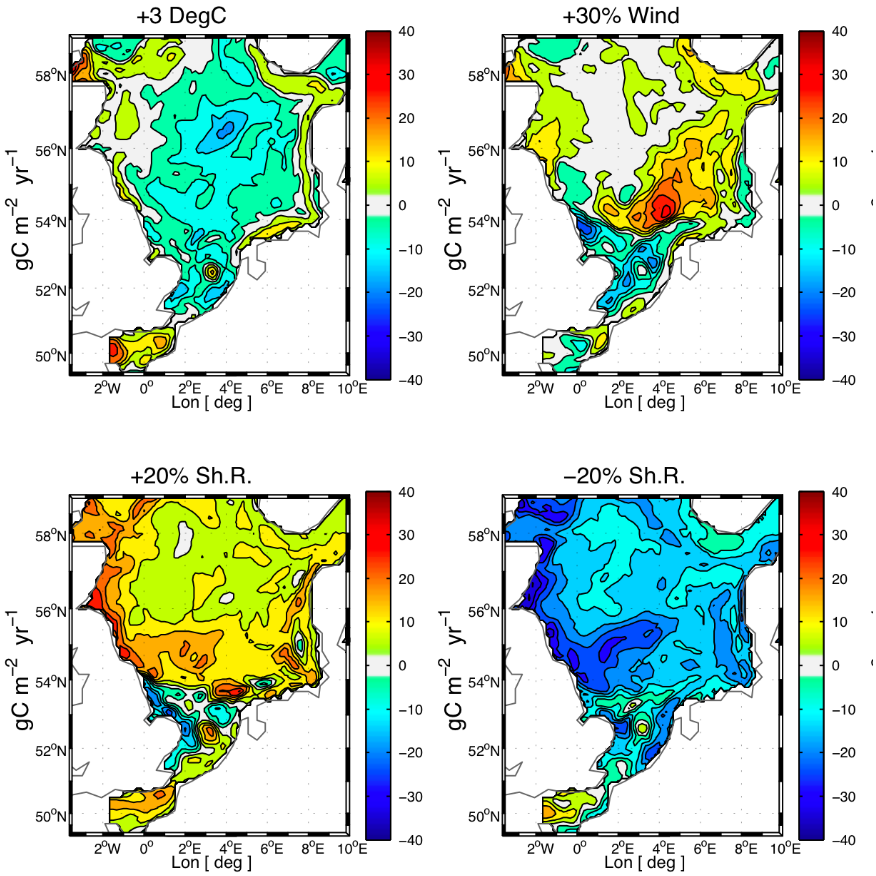

Figure 1 Changes in primary production (gCm^{-2}yr^{-1}) in response to an 3°C increase in temperature (upper left), a 30% increase in wind (upper right) and a 20% increase or decrease in radiation (Sh.R. bottom left and right) as predicted by the Ecosmo bio-physical model (Drinkwater et al., 2009. Deliverable 4.2).

Fish populations: distribution and productivity

Climate change can affect a multitude of environmental factors, that in turn may affect various processes at different levels of biological organisation (organism, population, ecosystem). Fish production is first of all dependent 'bottom up' on the production of algae in the ocean. On the other hand, the response of commercially-exploited fish species cannot solely be due to changes in their food resources, but may also be affected by direct effects on their physiology, or changes in ecosystem interactions (competitors and predators). Since fishing heavily impacts marine ecosystems through removal of individuals and physical abrasion of benthic communities, fisheries and climate will interact and both drivers need to be taken into account when attempting to resolve the impact of climate change on fish populations.

There is ample evidence for changes in distribution of fish populations in relation to climate. Figure 2 provides an example of the changes in distribution and abundance of a southern species, John Dory (*Zeus faber*). Species that have historically had a low- to mid-latitude distribution (often termed 'Lusitanian species'), tend to increase at the high latitudinal range of their distribution as temperatures warm, while species with a higher latitudinal distribution (often called 'boreal species') exhibit declines at their lowest latitudes. Also, changes in the bathymetric distribution have been reported with species shifting their distribution to deeper cooler waters. The underlying mechanisms of the distribution shifts, however, are less well known. RECLAIM has revealed that throughout the 20th Century, the centre of fish distribution, as reported by commercial fishermen, has changed appreciably in the northeast Atlantic, for example in North Sea cod have moved to the northeast, whereas plaice have moved northwestwards, sole have moved south towards the Channel (where conditions are now habitable throughout the winter), and haddock occupied the same area on average but their southern limit of distribution moved 130 km to the North over the past 80-90 years. For plaice, long-term climate change seems to have been the main cause of distribution shifts, but for sole both climate and fishing pressure seem to have had an important influence.

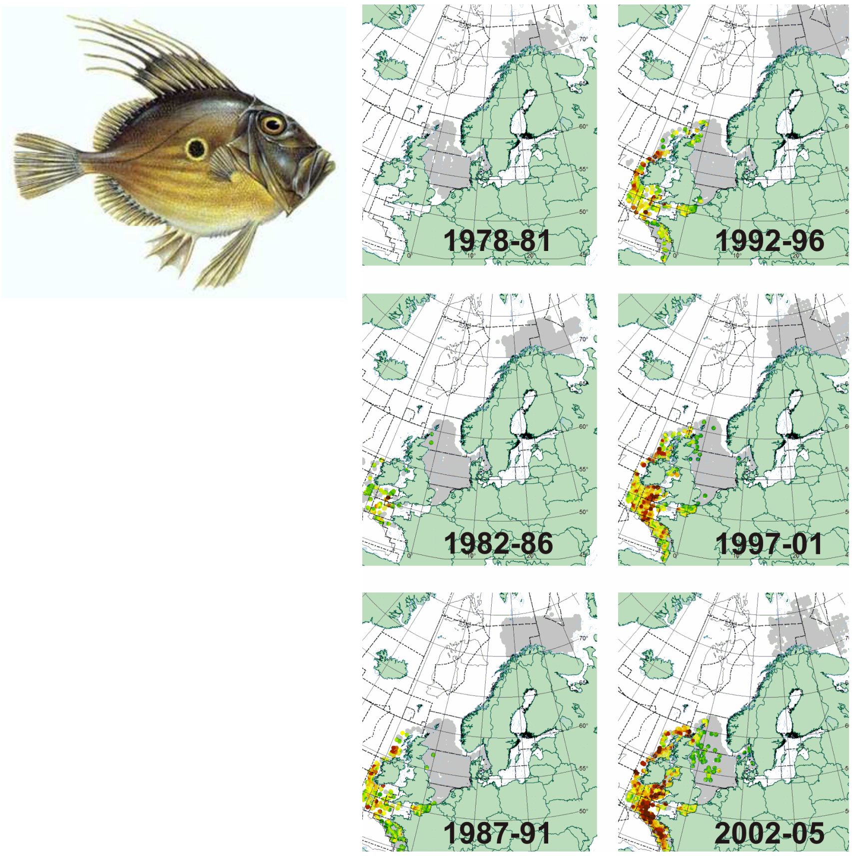

Figure 2 Change in abundance and distribution of John Dory (*Zeus faber*), a Lusitanian species (Pinnegar et al., 2009. Deliverable 1).

In analyzing climate impacts, RECLAIM has taken into account the fact that fish have complex life cycles that include various life stages (egg, larval, juvenile and adult) that may rely on different, spatially-separated habitats. Moreover, individuals undergo massive developmental and physiological changes as they progress through these stages (e.g., individuals often increasing in body size by a factor of 10^5 from egg to adults). RECLAIM utilised a variety of methods to reveal critical life stages (stages most sensitive to climate impacts) including analyses of the abundance and mortality across successive life history stages. There are very few species where there are sufficient data with which one can examine ‘critical life history stages’. It is clear that different factors are affecting each species e.g. in cod, cannibalism on age 0 fish, or larval starvation can be significant, whereas density-dependent factors can affect juvenile flatfish on an essentially two-dimensional nursery ground. A closer examination of North Sea herring highlighted the necessity to examine temporal changes in mortality schedules in relation to key ‘periods’ or windows of opportunity, i.e. there could be shifts in the underlying ‘productivity’ of the system that need to be recognized to be able to interpret changes in mortality.

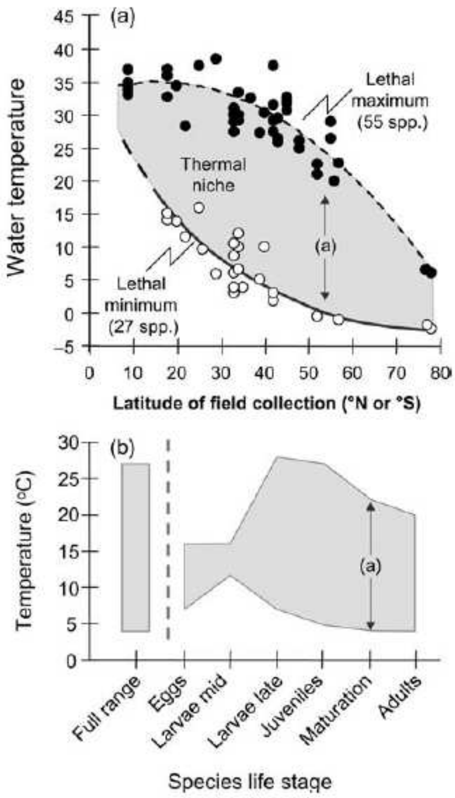

Figure 3 Diagram of the changes in suitable habitats (based on water temperature) with (a) latitude of the species and/or population and (b) by life stage. The arrow (a) denotes a range of tolerable temperatures measured for adults during maturation and spawning (from Rijnsdorp et al., 2009. ICES JMS 66: 1570-1583. Deliverable 1).

Knowledge on the eco-physiology of the various life history stages provide a solid foundation to evaluate the likely impact of climate change on fish more generally, and may provide insight into the relative sensitivity of different life stages (Figure 3). There is evidence that life stages differ in their sensitivity to environmental factors such as temperature. In terms of identifying critical periods, there was no common pattern among species with respect to changes in thermal tolerance among eggs, larvae, juveniles and adults. Spawning adults and/or early life stages (eggs and larvae) often exhibited the narrowest range of tolerable temperatures. Prey availability, particularly during the late larval and early juvenile period, appears to be one of the most important environmental factors creating density-dependent fluctuations in populations in both the northwest Pacific and Northeast Atlantic and this has knock-on implications for year-class-strength and commercial fisheries.

There is a lack of basic information on temperature tolerance and sensitivity for many species not to mention the impacts of “multiple stressors” (e.g., the combined effects of changes in temperature, salinity, and dissolved O_2 for Baltic Sea organisms) on the survival and/or other vital rates. Studies examining the impacts of multiple stressors on stage-specific vital rates would provide the most meaningful data with respect to ongoing, climate-driven changes in habitats.. The limited data indicate that the ranges in preferred temperatures and tolerable temperatures were positively related with optimal temperatures for growth suggesting that species with a large tolerance range had lower temperature sensitivity. No clear differences between pelagic and demersal species were observed.

Finally, changes in the adaptive capacity of fish (and other organisms) to changes in temperature and other abiotic factors are largely unknown. Physiological adaptation is possible and could mitigate (offset) the impacts associated with environmental change. Climate change may evoke concomitant evolutionary change as has been demonstrated in a variety of taxa. The situation is further complicated by a haemoglobin polymorphism in species such as cod that is expressed differently across the geographical distribution of the species. Studies examining the adaptive capacity of fish species and populations would clearly be beneficial to ongoing efforts to project climate-driven changes in distribution and productivity of fish populations by using techniques such as bio-envelope climate modelling. However, such techniques need to also consider the potential changes in the prey and predators of the species in question, habitat requirements and the connectivity between spawning and feeding grounds.

It is uncontested that simulation models that couple the physics of the ocean and the biology and ecological interactions among the species are indispensable tools in the study of climate change. State-of-the art in bio-physical models typically include nutrients, phytoplankton, zooplankton and detritus dynamics (NPZD-models), but rarely are these coupled to models of higher trophic levels (e.g. fish).

Within RECLAIM, NPZD-models were used to explore how climate-driven changes in bottom-up factors could impact on fish larvae (growth, mortality, transport) with comparisons made of modelled and observational data for plankton and fish larvae. Results suggests that climate driven bottom-up processes can have multiple, interacting impacts on the survival of the early life stages of marine fish species including: (1) species-specific changes in the match-mismatch dynamics of first-feeding marine fish larvae and their prey (zooplankton), and (2) changes in transport patterns of developing larval cohorts. Overall, the results indicated that continued warming will make vast areas of the North Sea unsuitable for species such as cod (winter-spring spawners) but will have little impact on species such as sprat (spring summer spawners). Also simulations suggested that the survival of Baltic sprat larvae will depend upon climate-forced changes in both temperature and prey populations. A study of larval herring in the North Sea, showed that the intensity and spreading of the autumn zooplankton bloom might be an important driver influencing maximum larval length and consequently their overwinter survival. NPZD modelling within RECLAIM also indicated that the direct response to increasing temperatures was stronger for zooplankton than for phytoplankton causing higher grazing impact on phytoplankton, faster recycling of nutrients and less sedimentation of organic matter to the sea floor. Climate warming is therefore expected to be more detrimental for benthic animals than for pelagic species. In another study requested by OSPAR, the interaction of increased temperatures and mandated nutrient reductions (50%-70% for N and P, respectively) to mitigate eutrophication were analysed on zooplankton and larval survival of different marine fish species. Model results suggest that changes in zooplankton production and, more importantly, species composition caused by changes in nutrient loading could have marked impact on trophic coupling between zooplankton and fish early life stages in the future.

Bio-physical (NPZD) models are generally restricted to the early life history stages of fish, and do not include juvenile and adult stages allowing an examination of how climate change could impact life cycle closure. Some biophysical lower trophic level models do not include benthic components of the ecosystem, making estimates of changes in energy flow (nutrient cycling) impossible. Within the benthic community, organisms with different feeding ecology will experience a varying degree of food limitation in a warmer climate. NPZD modelling showed that benthic suspension feeders that have access to suspended particulate organic matter in the bottom water were less influenced by the reduced sedimentation whereas the growth and productivity of deposit feeders living in the sediment were severely reduced. This may have consequences for fish species that are highly dependent on benthic deposit feeders as a food resource, for example sole and lemon sole, although they may be able to adapt by preying upon other benthic resources.

For a population to survive there must be life history closure, i.e., the whole life cycle must be able to be completed. Current coupled bio-physiological models are not equipped to deal with life-cycle closure in fish as they only address egg and larval life phases. In a first attempt to include later life history stages, a Dynamic Energy Budget (DEB) model of adult anchovy was combined with a NPZD-model to estimate spatial habitat suitability based upon energy available for spawning in the Bay of Biscay and the North Sea. The maps agreed well with the long-term patterns of anchovy presence, critical seasons and core habitats. A climate scenario suggested that the index of fronts did not change but the bottom temperature increased dramatically by approximately 2.5°C on the shelf in comparison to the reference. As a result, the mean predicted anchovy distribution was guided by the overall increase in temperature and showed anchovy dispersed everywhere with maximum concentrations along the coast (Figure 4). In particular, the shelf north of 46°30´N that was empty in the past is potentially opened to the anchovy under future climate change.

A further RECLAIM study used a delta GAM/GLM approach to model future plaice and red mullet distribution in the eastern English Channel and southern North Sea. Abundance of each species was related to depth, seabed sediment type, bottom salinity and temperature, primary production and zooplankton biomass using outputs obtained from the hydrodynamic and ecosystem model ECOSMO. Results suggest that climate change may strongly impact the future distribution of plaice. For large plaice (>18cm), distribution will still be centered in the southern part of the North Sea, however for young individuals, the predicted distribution is anticipated to shift northwestwards to the Dogger Bank area in particular. Small plaice (<18cm) are currently confined to the southern North Sea along the Dutch coast, a region that may become inhospitable in the near future. Red mullet abundance was again divided into small (<17.3cm) and large (>17.3cm) individuals. Currently a relatively small component of the red mullet population is known to overwinter in the North Sea. Model outputs indicate that that the distribution of adult red mullet will not change dramatically but that for small/young individuals, the offshore habitat situated on the Dogger Bank may become more favorable. Older individuals seem little impacted by changes in environment, but they may benefit from higher juvenile survival and expand their area of occupation as a result

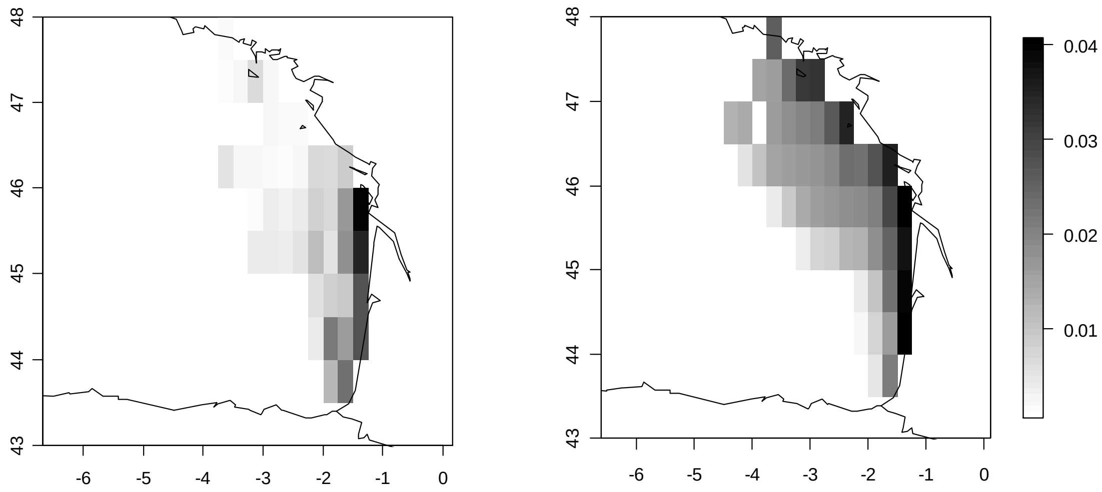

Figure 4 Modelled distribution of anchovy in the Bay of Biscay in 2050 under climate change (right hand panel) in comparison with the current distribution (left hand panel) (Petitgas et al., 2009. Deliverable 4.3).

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The implications of climate change for fisheries management was explored in Baltic cod (Figure 5). Climate change is expected to result in a warmer and less saline Baltic. The maximum sustainable fishing mortality (F_{msy}) is anticipated to decline with both decreasing salinity and increasing temperature. This can be explained by a direct salinity effect on cod recruitment (i.e., through egg and larvae survival) and an indirect temperature effect channeled through species interactions; due to increased recruitment of sprat and a competition driven decline in herring eventually affecting the dominance and availability of prey for cod. Hence, the degree to which species interactions may either buffer or accentuate the cod stock response to climate change depends on the nature of both positive and negative feedback loops within the food-web.

RECLAIM has provided considerable insight into the likely implications of climate change for marine fish and ecosystems, but it has thus-far provided only limited comment on the likely consequences of such changes for commercial fisheries and regional economies. We anticipate that climate change will have the following implications on fisheries, and urge that further research is needed in this area: (i) modelling of how fishers will respond to changes in fish distribution, including impacts on distance that fishers will need to travel to maintain catches (additional fuel costs, days at sea etc.), the potential impact on stocks that span national boundaries and consequences for quota allocation, the potential impact on marine-protected-area effectiveness if protected species move outside the boundaries of the closed area, e.g.

a potected nursery or spawning site; (ii) the potential impact of climate change on fish ‘catchability’, e.g. whether fish behave differently in warmer waters (whether they respond differently to an incoming trawl), whether the geometry of fishing gears will change as species and fisheries move into deeper waters, and the potential impact of ocean acidification on noise-transmission in the ocean, which could impact on the ability of fish to detect incoming trawls; and (iii) the socio-economic implications of changed fisheries yields associated with climate change. Yields are predicted to increase in the north but decrease in the south of Europe. Fishermen and fishery managers will need to consider how fleets can adapt to these changing opportunities, e.g. through targeting new (incoming) species, diversifying the portfolio of activities so they are not reliant on one vulnerable resource, moving elsewhere, or leaving the sector altogether (and diversifying into ecotourism or recreational fishing charters etc.).

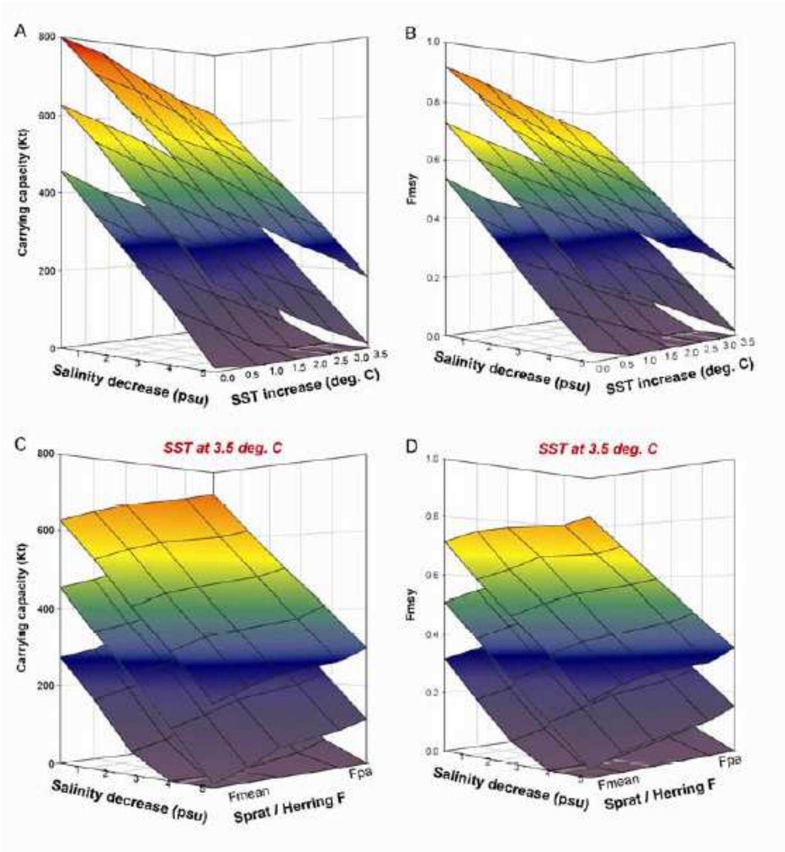

Figure 5 A sustainable management strategy for Baltic cod under different scenarios of climate change. In (A) and (B) the theoretical carrying capacity (K_t) and corresponding maximum sustainable fishing mortality (F_{msy}) for Baltic cod is shown for each combination of projected changes in salinity and sea surface temperature (SST). In order to address the indirect effects of species interactions on cod stock response to climate change, the lower panels (C, D) include fishing pressures for sprat and herring, given a projected increase in SST by 3.5°C. Fishing mortalities range from mean historical levels (F_{mean}) to the recommended precautionary levels (F_{pa}) for sprat and herring respectively. The middle planes represents mean K and F_{msy} while upper and lower planes respectively illustrate the upper and lower confidence levels of each scenario (Drinkwater et al. 2009; Deliverable 4.4).

Conclusion and recommendations for the future research agenda

Based on the results of the studies carried out in the various RECLAIM workpackages, as well as the results of the symposium on the "Effects of Climate Change on Fish and Fisheries: Forecasting Impacts, Assessing Ecosystem Reponses, and Evaluating Management Strategies" held in Sendai (Japan) in April 2010, RECLAIM proposes the following six recommendations for future research. The first recommendation is more generic while the next five recommendations are specific yet inter-related in that they all help fill gaps in knowledge on understanding and projecting climate-effects on marine fish and shellfish resources. In this regard, each recommendation carries the same rank in research priority.

1) In general, research proposals should be funded that utilized a variety of methodological approaches (field studies, laboratory experiments, modelling simulations) to project the impacts of climate change on fish and fisheries. There is ample evidence that climate change impacts the abundance, distribution, interactions and productivity of fish and shellfish stocks, but there is still much uncertainty about the mechanisms involved and our ability to project the biological consequences is limited. Climate change may impact different levels of organisation (organism, population, ecosystem) and does not occur in isolation of other global change factors. The future research agenda should stimulate projects that adopt a combination of different approaches such as conceptual predictions, inferences from laboratory studies and the application of models. Each of these approaches has strengths and weaknesses and play a different role. Future r*esearch needs to focus on the combined and interactive effects of factors such as fishing and acidification*.

Conceptual prediction, based on relevant biological and ecological mechanisms, is the first and most simple approach to predict how fish may respond to climate change. This approach also provides a valuable starting point for studies of specific mechanism to test a priori formulated hypothesis such as those presented in Appendix 1. The approach is qualitative and can be applied at the level of the organism, population and ecosystem and short- to long-term time scales. Specific research priorities for laboratory, field and modelling research are listed below.

2) Laboratory studies, in particular eco-physiological studies, provide the basis for the understanding the response of organisms to changes in key environmental factors and for formulating and parameterizing models. Very little work has been carried out on fish ecophysiology since the 1970s and yet such information is becoming increasingly useful as researchers attempt to predict the future implications of climate change. Priority should be given to commercially-important species and species that play a vital role in the ecosystem. This is a priority research area stemming from:

2.1) the clear lack of experimental studies on the eco-physiology, growth and survival of organisms in relation to temperature, oxygen, salinity and pH, factors most relevant in relation to climate change, and their combined effects (multi stressors).

2.2) *the current, poor understanding of the evolutionary adaptive capacity of marine fish populations and their predators and prey to climate-driven change in environmental factors*

3) Global Circulation Models (GCM) provide indispensable tools for the study of climate change impacts on fish and shellfish populations by providing estimates of

historical and current physical and chemical conditions in the ocean and projecting how those factors may be altered in light of climate change. The current GCMs are unable to adequately capture relevant features such as the decadal (NAO) and multi-decadal (AMO) variability associated with historical changes in ecosystem functioning. Thus, high research priority areas include:

3.1) *improvements of GCMs need to be made so that these models adequately capture the (multi-) decadal variability historically observed in the coupled atmosphere-ocean system but also important features such as changes in wind and storms*.

Moreover, in order to make realistic projections of impacts at smaller (ecosystem) scales:

3.2) *regional dynamic downscaling methods need to be advanced preferably in an ensemble manner using a variety of different GCMs in order to avoid model-specific problems and increase confidence in projections of future ocean climate.*

4) Models that close the life cycle of single species, consider inter- and intra-specific interactions of various life stages, and capture end-to-end ecosystem structure and dynamics need to be developed, validated and implemented. The results of fisheries oceanographic research programs and laboratory studies are critical *to building integrated biological and oceanographic models*, evaluating species environmental tolerances and adaptation, and tracking species responses to long-term ecosystem and climate change. In terms of ecosystem dynamics, climate-driven changes in bentho-pelagic coupling and lower trophic levels are critical to the productivity of higher trophic levels. Together, with changes in patterns of exploitation of higher tropic levels, these processes will affect the structure and dynamics of entire marine food webs and production on all trophic levels. Integrated, ecosystem-level projections of climate impacts thus require "end-to-end" models. When examining key (fish) species, bio-physical models have been extensively utilized for study of eggs and larvae that provide a strong basis for projecting how climate change will impact the survival of these "passive" early life history stages. However, climate change may deleteriously impact the vital rates of other life stages, altering e.g. recruitment dynamics. In terms of biophysical modelling of marine systems and species, high research priorities include:

4.1) *Lower trophic ecosystem models need to be improved to include more emphasis on pelagic-benthic coupling in shelf sea systems*.

4.2) *Extension of single-species, bio-physical models beyond the egg and larval stages to close the life cycle in order to better project climate-driven changes on marine fish populations stemming from processes acting directly on various life history stages (from eggs to adults) or indirectly via changes in key stage-specific habitats.*

4.3) *Models to describe and project predator-prey interactions, explicitly considering spatial and temporal dynamics in abundance, key population dynamics rates and productivity*, are needed to establish how changing marine communities might interact and food webs develop..

4.4) *End-to-end ecosystem models* can build upon advancement made in modelling specific components of ecosystems to quantify how climate-driven physical and biogeochemical changes will be transmitted to changes in the trophodynamic structure and function. Such models should depict changes at all levels of the food web (e.g., from primary and secondary production to top-level consumers). *Linking key* *components of upper and lower trophic levels* will ultimately be necessary to accurately project the consequences of climate change for higher tropic level consumers and ecosystem properties (such as biodiversity) as well as feedbacks from alterations in higher trophic to lower trophic levels including their ability to sequester carbon impacting on the earth climate.

4.5) *In all of these cases (4.1-4.4), modelling studies should particularly address uncertainty* (parameter uncertainty, structural uncertainty and scenario uncertainty) to provide confidence limits on their projections.

5) Long-term monitoring programs are essential to track the changes in ocean climate and the ecosystem, and provide the background for the calibration of the models. Long-term records (decades to centuries) often indicate large-scale fluctuations in the productivity and/or distribution of particular species or species groups allowing the magnitude of "natural" fluctuations to be reconciled against more recent changes caused by anthropogenic activities. Shorter-term, higher resolution time series allow issues such as "non-stationarity" in causal processes to be addressed. Field sampling programs appear to be under-funded in lieu of funding for programs exploring modelling approaches. There is often a mismatch in model resolution (high) and field data resolution (low) making the validation of models extremely challenging if not impossible. A high research priority is to:

5.1) *Extend and integrate ongoing environmental and biological monitoring programmes to* ***simultaneously*** *cover physical and chemical oceanography, plankton, benthos, fish, and potentially birds and marine mammals. Developing benthos sampling program components appears to be particularly important as long-term benthic data series are largely lacking.* Similarly time series of fish stomach contents data (as larvae, juveniles and adults) would be useful in order to determine interdependencies and possible indirect consequences of future ecosystem change.

5.2) *Design and implement field research technology sampling at both large and small spatio/temporal scales that utilize traditional (net) as well as innovative (video imaging, hydroacoustic, DNA microarray) techniques and gears.* The emphasis should be placed on collecting data sufficient for the validation of process, species and ecosystem models (e.g., year-round standing stocks, phenology of production, and trophodynamic interrelationships). The latter is particularly important given observed changes in the distribution and species composition (and likely species interactions) within areas such as the North Sea.

6) Climate-driven changes in key fisheries resources must be placed within a broader context of fisheries management and marine spatial planning, such that costs and tradeoffs of various exploitation and management strategies can be weighed in light of changes in the productivity and distribution of fisheries resources. In this regard, holistic modelling approaches are needed that build upon the experience of (often disparate) sectors. Similarly, more understanding is required of how fishers might respond to such changes, by adapting their behaviour, targeting strategies, compliance, equipment or fishing location. World-wide, very few examples of this approach exist. Therefore, a high research priority is to:

6.1) *build, validate and utilize integrated monitoring programmes and data handling structures as well as models that consider social and economic responses to changes in marine fish and their fisheries including activities in other sectors*. Such tools will be indispensable for future ecosystem-based management. So far the European Union and national governments have funded a surprisingly small amount of research on the implications of climate change for fisheries, fishermen and local economies, despite the growing body of work on fish and climate change.

Appendix

Working hypothesis

RECLAIM has formulated six (sets of) working hypothesis based on a priori mechanistic arguments. These working hypothesis will be useful to analyse the processes that underlie the response of fish and shellfish populations to climate change and will improve our capabilities to predict the implications of future climate change.

(1) The response of fish populations to climate change will differ between species as well as between stocks across the geographical distribution area. This leads to the first set of working hypotheses:

H1a. Populations at the limits of their latitudinal range will show stronger responses than those occurring within habitats in the centre of their latitudinal distribution;

H1b. Northerly species at the southern limits of their distribution will decrease in abundance and southerly species will increase at their northern limits;

H1c. Species distributions will shift to deeper, cooler waters in response to an increase in water temperature.

H1d. Climate change will result in an increase in biodiversity (species richness).

(2) We expect that the response of species to climate change will be influenced by their habitat requirements (pelagic, demersal, deepwater species), life history characteristics (short-or long-lived; specialist or generalist), and trophic position within the ecosystem (apex predators or forage fish). This leads to the following hypotheses:

H2a. Species with habitat requirements at fixed geographic locations will differ in their distributional responses in comparison with species that are linked to open water masses.

H2b. Deep-water fish species will be less impacted by climate change in comparison with shelf or coastal species;

H2c. Fish species with narrow dietary preferences will be more sensitive to climate change, compared with generalists;

H2d. Short-lived species will show stronger responses and will be better equipped to adapt to changes in their environment than long-lived species.

(3) Populations can survive in systems where suitable habitats for the different life history stages are available and are connected, allowing life cycle closure. If the habitat for a certain life stage is spatially restricted, a change in habitat suitability of this stage will make the species more sensitive to climate change than species which do not have spatially restricted habitat requirements. This leads to the following hypotheses:

H3a. Species with spatially restricted habitat requirements during part of their life history will be more sensitive to climate change than species without specific habitat requirements.

H3b. Fish populations in oceanographic systems with a high variety of mesoscale features will show less influence of climate change.

(4) Fishing will reduce the size- and age-structure of a population and reduce its bet-hedging capabilities that would allow it to successfully contend with variability in suitable conditions for the survival of eggs and larvae. Also, fishing may lead to a reduction in genetic variability that would negatively impact the possibilities of an evolutionary response to climate change and the ability of depleted stocks to recover.

H4. Fish stocks under intense exploitation will be more vulnerable to climate change than those experiencing low fishing pressure.

(5) The ecosystem response to climate change will depend on the response of the individual species and the resulting effect on trophodynamic interactions among species.

H5a. Ecosystems with simple trophic structure will show more rapid responses to climate change than ecosystems with more complex trophic structure and many alternative prey types.

H5b. Changes in ecosystem structure caused by climate change will be non-linear and abrupt.

H5c. Under climate change we expect the pelagic productivity to go up and the demersal productivity to go down.

H5d. Increased species richness will result in an increased importance of bottom-up processes.

(6) Improved environmental conditions, as well as new shipping routes, will facilitate the spread of warm-water fish species and pathogens.

H6. With improved local conditions, an increased number of exotic warm-water fish species (and fish pathogens) will become established in European waters.