Climate change and European fisheries: observed changes and future prospects

EFARO Position Paper, August 2012

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This text prepared for EFARO by John Pinnegar (CEFAS)
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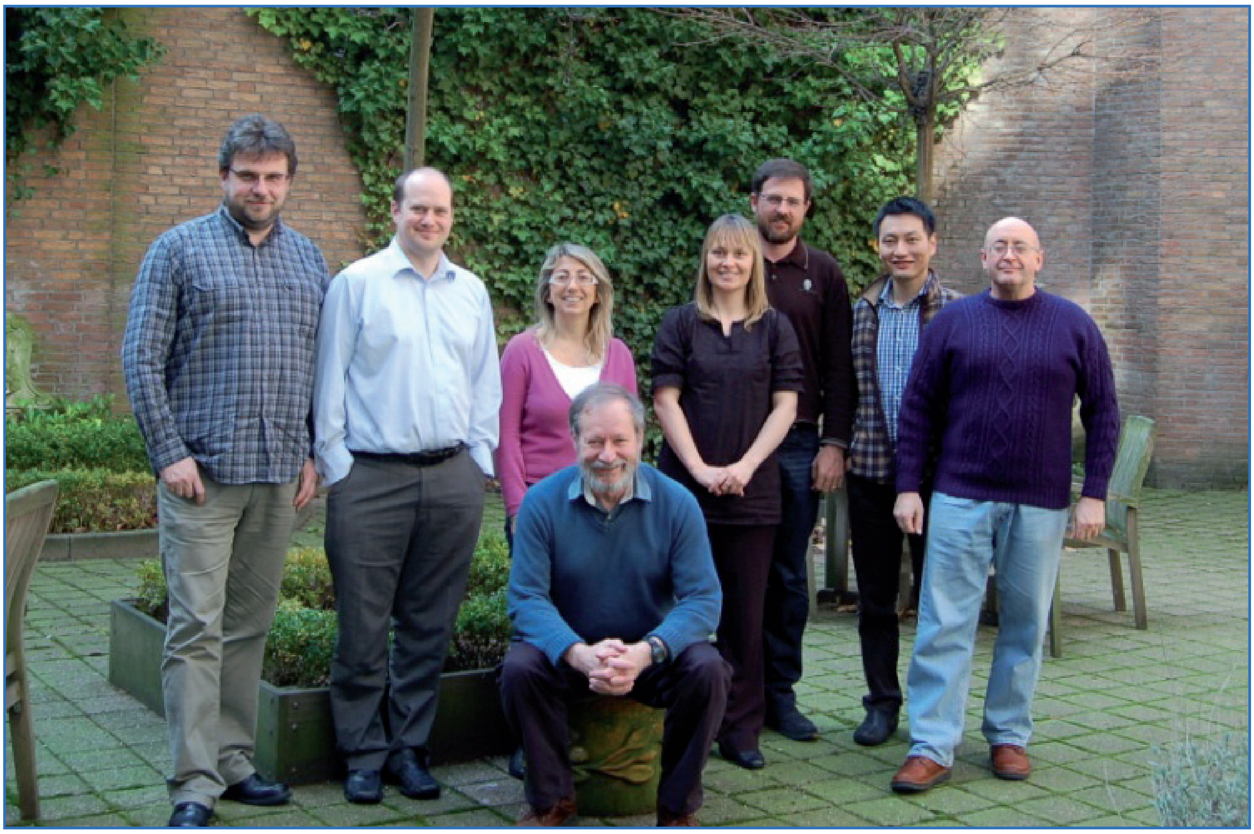

EFARO Climate Change Workshop, 14-15 March 2011, Amsterdam
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Knowledge gaps and key recommendations identified in the report

Detailed discussion of knowledge gaps and recommendations are given in section 7. A brief overview of the key priority area is given in the table below. In order to rank topics a simple scoring exercise has been carried out on the basis of urgency/immediacy and relevance. Research themes were also categorised according to perceived 'value for money'(VFM), and their match/relevance to the stated objectives and remit of EFARO (i.e. to promote scientific cooperation in the area of fisheries and aquaculture specifically)

Each 'knowledge gap' is accompanied by a recommendation referenced in column 1 describing the research required. An additional column was added to the table providing insight into the perceived maturity of the knowledge base in each case. For example studies linking fish recruitment to climate have been conducted for more than 50 years and this topic has scored '5', whereas detailed studies on ocean acidification have only been carried out within the past 5-10 years and this topic has been scored '1'.

When attempting to prioritise the research gaps that need to be addressed, a useful approach is to look for those that score highly in terms of immediacy, value for money and relevance, and compare this score with the maturity of the knowledge base, such that those that offer the highest overall score in terms of importance and the lowest in terms of current knowledge should be particularly prioritised. A good example of this is knowledge gap "3A" *Modelling the behaviour of fishers*.

Prioritised list of research gaps

Rec No	Knowledge gap	VFM	Im-mediacy	Rele-vance	Wider Benefits	Score	Existing science
4D	Trade-offs between fisheries, conservation and other human activities	4	5	5	4	18	2
3A	Modelling the behaviour of fishers	4	5	5	3	17	1
2E	Fisheries in the Arctic	4	4	5	4	17	1
2B	Understanding & modelling fish behaviour	3	5	5	4	17	3
2H	Ecosystem productivity and carrying capacity	4	5	5	3	17	3
3C	Impacts of climate change on recreational fisheries	4	4	5	3	16	1
1D	Understanding low oxygen events and their consequences	4	3	4	4	15	2
1C	Long-term datasets for climatic monitoring and model validation	5	3	2	5	15	3
2C	Scaling up from OA lab experiments to populations and ecosystems	4	2	5	3	14	2
3B	Adaptive capacity in fishing communities	4	2	4	4	14	2
2G	Biological/ecological data recovery	4	2	4	3	13	4
3D	Adaptability of international fisheries management	4	3	4	2	13	2
3E	Catchability and behaviour of fish in response to fishing gear	2	4	3	4	13	2
1E	Catchment to coast issues	3	2	4	3	12	2
2D	Understanding & predicting changing species interactions	2	2	4	4	12	3
2I	Understanding recruitment uncertainty	3	2	5	2	12	5
4C	Models that consider multiple stress factors	3	2	3	4	12	2
5A	Stakeholder participation and fisheries governance	2	4	3	3	12	3
4F	Aquaculture, fisheries & climate change	3	3	3	3	12	3
1A	Improved Regional Climate Models (RCMs)	3	2	2	4	11	4
2F	The spread of non-native/invasive species	3	3	3	2	11	2
2A	Biological adaptability to climate change	2	1	3	4	10	1
4A	Global economics & trade	2	2	3	3	10	3
4E	Data recovery - socio-economic	3	2	3	2	10	3
1B	Improved Global Circulation Models (GCMs)	1	1	1	5	8	5
4B	Carbon budgets (emissions from fishing vessels, natural sources & sinks)	3	1	1	3	8	2

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I Overall introduction

Recent reviews for the North Atlantic provide strong circumstantial evidence to suggest that changes in ocean climate will have far-reaching impacts on the dynamics of fish populations and consequently on future prospects for fisheries and aquaculture in Europe (e.g. Cheung et al. in press; Heath et al. in press). However, knowledge of the underlying mechanisms is rather limited. First, there is uncertainty about the future development of the ocean climate itself, as various aspects will be influenced such as circulation patterns, air and sea surface temperatures, frequency and intensity of storms, precipitation patterns, pH and river run off. Second, fish and shellfish typically have complex life cycles comprising several life history stages, differing in their sensitivity to climate effects.

The knowledge-base with regard to understanding interactions between fisheries and climate is growing, but there remain many challenges, especially with regard to predicting future socio-economic consequences. This position paper is not intended to be an exhaustive scientific review on the effect of climate change on fisheries, rather it aims to highlight some of the key issues and knowledge gaps, that fisheries fesearch institutes and the European Commission should aim to address in the near future.

2 Introduction to climate change (the physical basis)

Most marine life is sensitive to temperature and many marine organisms have life cycles adapted to a certain temperature range. Surface temperatures (SST) are increasing in all of Europe's seas. The changes have been up to six times larger than the global average over the past 25 years. The most rapid warming trend has been observed in the Baltic and North Seas, whereas the rates of increase are lower in the Black and Mediterranean Seas (Figure 1).

Carbon dioxide (CO_2) concentrations in the atmosphere increased during the last century due to a combination of industrialization, urbanization and deforestation and are continuing their rapid rise during the present century. The global response of atmospheric variables such as temperature, winds, precipitation (rain and snow), water vapor and atmospheric pressure to the increasing CO_2 can be examined using coupled ocean/atmosphere/sea-ice/land models. These Global Circulation Models (GCMs) suggest that the present observed warming can only be explained by anthropogenic forcing and they anticipate further warming world-wide throughout the present century due to the high levels of greenhouse gas emissions (IPCC, 2007). Precipitation and wind fields are also projected to change in future but with the sign and the amplitude of the change varying spatially. These atmospheric changes will impact the oceans, affecting hydrographic properties, currents and ultimately, marine resources.

The horizontal spatial resolution of GCMs has generally been too coarse (typically grid sizes of 200-400 km)

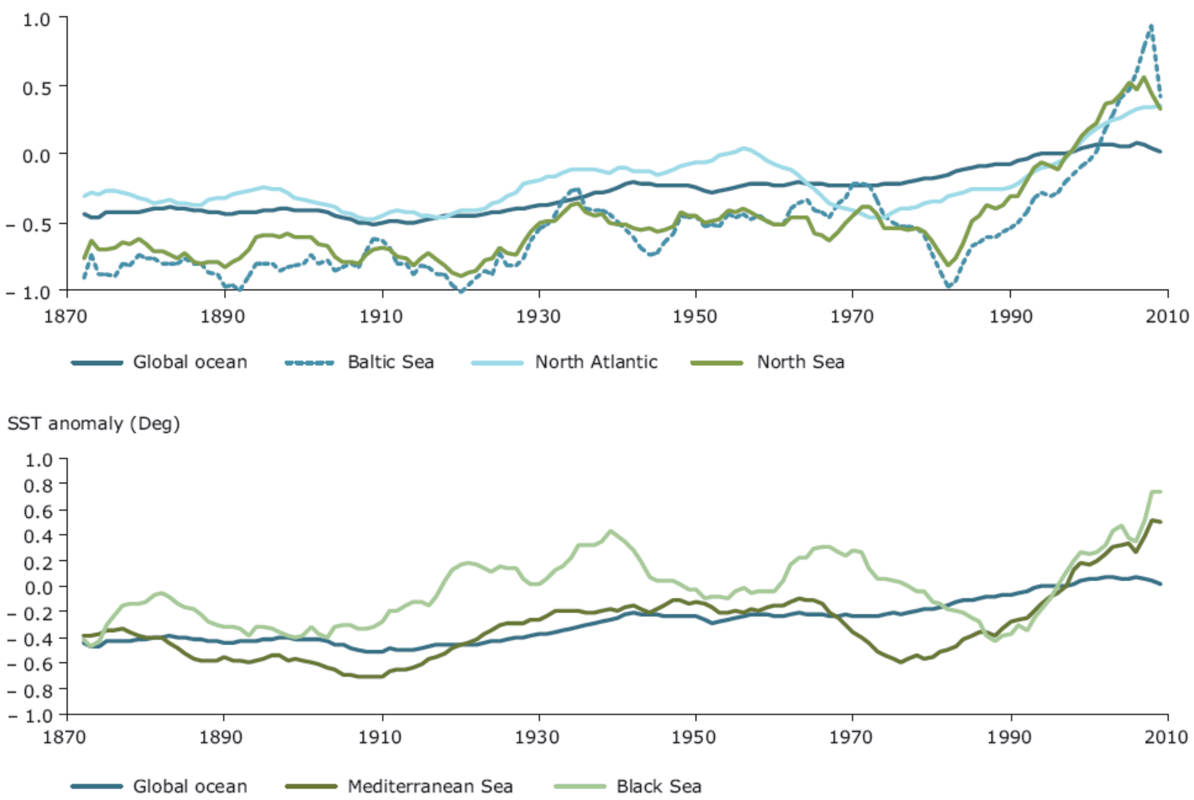

Figure 1.
Changes in surface temperature of European seas (SST anomaly, °C). Data show the difference between annual average temperatures and the 1982–2010 mean (European Environment Agency 2010).

to adequately resolve local or regional topography and ocean dynamics, especially features that impact fish populations such as upwelling, eddies, fronts, etc. For regional and local impact studies, therefore, the approach has been to develop higher resolution (typically grid sizes of 1-20 km) Regional Climate Models (RCMs), using the results from the GCMs as boundary conditions (termed "downscaling").

Climate is characterized in terms of long-term (typically 30-year) averages of elements such as temperature, precipitation, winds, etc. **Climate variability** is the temporal variation around this average state and is associated with time scales of months to millennia and beyond, i.e. longer than those associated with synoptic weather events. Natural climate variability refers to climate variations because of changes in solar radiation, volcanic eruptions, or internal dynamics within the climate system, while human effects on climate, such as those due to greenhouse gas emissions or land use change, are termed anthropogenic influences. **Climate change** is any systematic change in the long-term statistics of climate elements owing to differences in the mean level, the characteristic variability, or both. Climate change arises from both natural and anthropogenic causes but in recent years this term has been often applied to the latter only by the media, in policy documents, and in some scientific literature. Climate change in this sense has also been used interchangeably with global warming.

Ocean acidification is increasingly being viewed as a major threat to marine ecosystems, and yet the issue only came to public attention less than ten years ago. Ocean acidification is the name given to the ongoing decrease in the pH of the Earth's oceans, caused by their uptake of anthropogenic carbon dioxide from the atmosphere. Ocean acidification is not considered a part of 'climate change' *per se*, however it has come to be widely regarded as "the other carbon-dioxide problem" and has gained an increasing profile among international policy makers. Since the industrial revolution began, it is estimated that surface ocean pH has dropped by slightly more than 0.1 units on the logarithmic scale of pH, representing an approximately 29% increase in H+ concentrations. It is estimated that pH will drop by a further 0.3 to 0.5 pH units (an additional doubling to tripling of today's post-industrial acid concentrations) by 2100 as the oceans absorb more anthropogenic CO_2. It is believed that the resulting decrease in pH will have serious negative consequences, primarily for oceanic calcifying organisms. These span the food chain from autotrophs to heterotrophs and include organisms such as coccolithophores, corals, foraminifera, echinoderms, crustaceans and molluscs. Many of the impacted organisms are important for fisheries and aquaculture (see below) and consequently ocean acidification may pose a significant, though long-term, threat to the maritime economy.

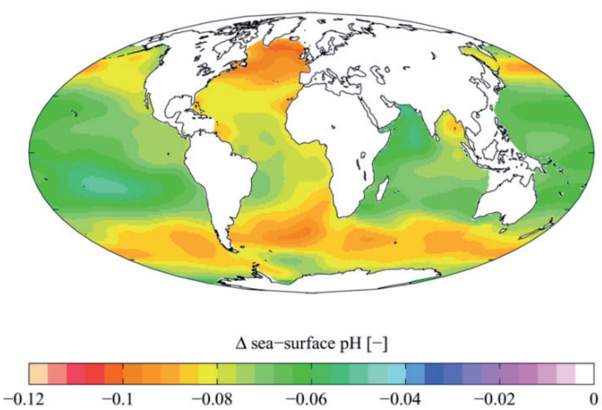

Figure 2.
Estimated change in annual mean sea surface pH between the pre-industrial period (1700s) and the present day (1990s). Δ pH here is in standard pH units.

3 Scope of this report

In this report we consider the potential implications of climate change and ocean acidification for fisheries in the European Union. European fisheries are incredibly diverse ranging from highly industrialised pelagic fisheries to small-scale artisinal fisheries that exist throughout much of the Mediterranean. European fishermen operate from the high arctic all the way to the tropics. Many EU member states have long traditions as distant-water fishing nations, most notably Spain, Portugal, France, Poland, and more recently the Netherlands. Currently, EU fishing fleets are active throughout all FAO regions of the Atlantic Ocean as well as the western and southern parts of the Indian Ocean, and increasingly in the Pacific region. Consequently some climate change impacts are viewed from a global perspective, and this review draws on wider climate change literature.

The assessment below provides a brief overview of observed changes in fish behaviour, distribution and physiology that are explicitly linked to climate change and are known to have impacted European fishing fleets over recent decades. It is important to note that we have not endeavoured to deliver an exhaustive review of fish biology, but rather we have concentrated our attention on more 'applied' topics that have a direct relevance to fleets, the operation of fishing gears and fishery catches in the future. We have restricted our overview to marine fisheries, and we have not addressed aquaculture in any great detail (since this would merit a detailed review of its own, e.g. Callaway et al. in press). We have paid particular attention to the few studies that have attempted to make projections of fisheries in the future as well as socio economic studies that have looked at possible consequences for fisheries governance, revenues and management.

Managers of marine fisheries in Europe have thus far paid little attention to recreational fisheries, though recreational fishing constitutes a considerable social and economic activity. Total expenditure on recreational fishing across Europe is believed to exceed 25 billion a year (Dillon, 2004), by comparison the 2007 value of commercial landings in the 27 EU member states was estimated at 6.2 billion. In this report we give some consideration to possible impacts of climate change on recreational fisheries, although we recognise that this is an area that has received very little scientific attention to date.

4 European fisheries policy in relation to climate change

The European Commission has announced that it is preparing for a fundamental reform of the Common Fisheries Policy (CFP) with the aim of achieving a genuinely viable and sustainable EU fishing industry and the further development of an Integrated Maritime Policy.

The 2009 Green Paper on 'Reform of the Common Fisheries Policy' recognized that *"Climate change is already having an impact on Europe's seas and is triggering changes to the abundance and distribution of fish stocks"*. It suggested that *"The new Common Fisheries Policy has to play a role in facilitating climate change adaptation efforts concerning impacts in the marine environment. Climate change is an added stress on marine ecosystems which makes a reduction of fishing pressure to sustainable level even more urgent"*.

The Green Paper also recognised that *"policy decisions must be based on robust and sound knowledge of the level of exploitation that stocks can sustain, of the effects of fishing on marine ecosystems and on the impacts of changes such as climate change"*. The reform of the CFP will be completed by the end of 2012, consequently there is a growing interest among European Policy makers in climate change adaptation measures, as well as threats and potential opportunities that might arise as a result of climate change and associated shifts in fish distribution.

The aim of the European Union's ambitious Marine Strategy Framework Directive (adopted in June 2008) is to protect more effectively the marine environment across Europe. It aims to achieve 'good environmental status; of the EU's marine waters by 2020 and to protect the resource base upon which marine-related economic and social activities depend. The Marine Strategy Framework Directive (MSFD) constitutes the vital environmental component of the Union's maritime policy. Within the MSFD it is noted that *"In view of the dynamic nature of marine ecosystems and their natural variability, and given that the pressures and impacts on them ……, it is essential to recognise that the determination of good environmental status may have to be adapted over time."* Indeed, this directive specifically outlines a requirement (Qualitative Descriptor number 1) that *"The quality and occurrence of habitats and the distribution and abundance of species are in line with prevailing physiographic, geographic and climatic conditions"*. This is being taken to mean that targets and limits (such as those used to manage fisheries) should be periodically reviewed to ensure that they continue to be effective even if underlying environmental conditions change.

Traditionally the 'Holy Grail' in fisheries science has been to try to find the maximum sustainable yield (MSY), i.e. the level of catches that can be sustained without irrevocably damaging the stock and causing the population to collapse. The World Summit on Sustainable Development, Johannesburg 2002 required that *"stocks should be recovered to levels that can produce maximum sustainable yields (MSY) by 2015"*. However, there are well-documented problems with the definition and performance of MSY targets in fisheries; especially where there are natural fluctuations in the resource, e.g. associated with climate variability and long-term climate change (see Mace 2001, Powers 2005). Cook & Heath (2005) examined the relationship between sea surface temperature and year-class-strength in a number of North Sea fish species and concluded that climate change has been 'eroding' the maximum sustainable yield of cod at a rate of 32,000 t per decade since 1980. Calculations show that the stock, could still support a sustainable fishery under a warmer climate but only at very much lower levels of fishing mortality, and consequently that current 'precautionary reference' limits or targets (e.g. F_{MSY}), calculated on the basis of historic time-series, may be unrealistically optimistic in the future.

The United Nations Agreement on 'straddling stocks' came into force in 2001 and includes explicit recognition of climate variability and change. The Straddling Fish Stocks Agreement was created to enhance the cooperative management of fisheries resources that span wide areas, and are of economic and environmental concern to a number of nations. Under Article 6, Member States are required to take into account of "existing and predicted oceanic, environmental and socio-economic conditions"; in Annex 1, Article 3 - states are required to conduct "research on environmental factors affecting stock abundance, and oceanographic and ecological studies".

5 Anticipated Ecosystem Impacts

Distribution shifts and the potential for international conflicts

Temperature is one of the primary factors, together with food availability and suitable spawning grounds that determine the large-scale distribution patterns of fish. Because most fish tend to prefer a specific temperature range, an expansion or contraction of the distribution range often coincides with long-term changes in temperature and/or climate. Perry et al. (2005) demonstrated that distributions of both exploited and non-exploited North Sea fishes have changed markedly over the last 25 years in the North Sea. These authors concluded that further temperature rises are likely to have a profound impact on commercial fisheries through continued shifts in distribution and alterations in community interactions. Distribution shifts may have 'knock on' impacts in terms of the 'availability' of animals to fishing gears, i.e. their 'catchability'. Populations may move away from (or towards) the area where fishing fleets operate and/or where spatial restrictions on fishing are in place. Also, species distributions may migrate across the boundaries where quotas belong to different nations. A notable example might arise as a result of quota allocations between Norway and the EU, or between Iceland and the EU. If, for example, species such as mackerel, blue whiting or herring move away from the EU sector, then EU fisheries may no longer be able to catch their full quota within indigenous waters, and hence there will be difficult political negotiations between nations with regard to future access to key fish stocks (e.g. Sissener & Bjorndal 2005). International law provides that coastal States have sovereign rights to manage fisheries in waters under their jurisdiction. With future climate change, we might anticipate more territorial disagreements of this type, and indeed in October 2009 North Sea Mackerel appeared to have moved away from the Norwegian Sector of the North Sea towards the Scottish coast, resulting in disagreements over permissible catches by Norwegian boats in EU waters. Norwegian vessels were forcibly escorted from Scottish waters by UK patrol vessels once they had caught their allotted quota (see *Fishing News*, 9th October 2009), but at the same time Iceland and the Faeroe Islands unilaterally claimed quota for mackerel, since the species had attained high abundance in their indigenous waters. This was subsequently challenged by EU fisheries ministers.

Theoretically, in the northern hemisphere, warming results in a distributional shift northward, and cooling draws species southwards. Recent analyses of Scottish and English commercial catch data spanning the period 1913-2007, (see Engelhard et al. 2011) has revealed that the peak catches of target species such as cod, haddock, plaice and sole, have shifted but not necessarily in a consistent way. Cod distribution seems to have shifted steadily north-eastward, towards deeper water over the past 9 decades, whereas plaice distribution has moved north-westwards, and this confirms the findings of van Keeken et al., (2007). Haddock catches have moved very little in terms of centre of distribution, but their southen boundary has shifted northwards by approximately 130 km over the past 80-90 years. Sole seem to have retreated away from the Dutch coast, southwards towards the eastern Channel, illustrating the fact that climate change related distribution shifts in European waters are not a straightforward issue.

Distribution changes may have significant consequences for the distance that must be travelled by fishing boats to reach the target resources with implications for fuel usage and time at sea. In addition, increased or reduced storminess could impact the ability of fishing boats to access resources in the future, which may be further constrained if a 'days at sea' based management regime is in place. The Nordic Seas, which include Greenland, the Norwegian Sea and Iceland, are a transition zone for warm and saline Atlantic water on its way to the Arctic, and for cold and less saline deep waters flowing from the Arctic to the Atlantic Ocean. Large ecosystem changes have been observed in this ecoregion in the recent past. For example, the abundance of Norwegian spring-spawning herring increased during the warming of the 1920s, decreased during the cooling period in the 1960s but has risen again since the temperature increases of the 1990s (Toresen and Østvedt 2000). Much has been written about climate change and the distribution of cod in the Nordic Seas region (e.g. Sundby & Nakken 2008). Arcto-Norwegian cod tend to produce strong year classes in warm years and poor year classes in cold years. Along the Norwegian coast, cod spawning grounds tend to be displaced to the north during warm periods (1910-1940s, and 1980 to present) but spawning occurs further south during cold periods (e.g. 1950s to 1970s). After 1976, qualitative observations show that there have been poor spawning in the southernmost spawning areas but from 2003 onwards, spawning has been observed along the coast of East Finnmark in the far North where it did not occur previously (e.g. Sundby & Nakken 2008).

In the Western Mediterranean, climate change has been shown to affect the boundaries of biogeographic regions, with some warm water species extending their ranges and colonising new areas in recent years where they were previously absent (Philippart et al. 2007). Sabatés et al. (2006) analysed temporal and spatial changes in abundance and distribution of *Sardinella aurita*. In the western Mediterranean basin (1950–2003), a significant positive relationship was found between sardinella landings and temperature anomalies. Along a latitudinal gradient off the Mediterranean Iberian coast (1989–2004), a gradual increase in species abundance was observed from south to north, whereas in the Aegean Sea the geographic distribution of sardinella, as reflected in purse-seine catches, has gradually expanded northwards in association with warming seawater temperatures since the early 1990s (Tsikliras 2008).

Incoming species and new opportunities

European fishermen have witnessed and responded to a number of new opportunities in recent years, as warm-water species have moved northwards and their exploitation has become commercially viable in new areas for the first time. Notable examples include new and/or expanding fisheries for seabass, red mullet, anchovy and squid, all of which are 'southerly' species that have expanded their distribution into more 'northerly' waters such as the North and Irish Seas.

In Ireland, new fisheries have recently opened up for boarfish *Capros aper*, a small, previously unimportant animal that is converted to fish meal for aquaculture. Landings have grown rapidly from less than 120 tonnes in the year 2001, to more than 139,000 tonnes in 2010. Both Irish and Danish fishermen have invested in new technologies to successfully catch and land the stock, and in addition Irish fishermen also invested in scientific research to increase knowledge of the biology and dynamics of this resource (White et al. 2010). This fishery is now worth more than 4 million, yet the fishery only became commercially viable following a sudden expansion of the species in the early 1990s. Boarfish became increasingly prevalent in French and UK survey catches after 1991 (see Pinnegar et al. 2002), and this phenomenon has been reported as occurring simultaneously elsewhere in the North Atlantic including the Bay of Biscay (Farina et al. 1997; Blanchard & Vandermeirsch 2005), the Gulf of Lion (inside the Mediterranean; Abad and Giraldez 1990) and on offshore seamounts (Fock et al. 2002). In the past *C. aper* outbreaks had been linked to storms and variability in offshore climate (Cooper 1952). Their appearance after 1991 across whole ocean basins may be linked to a series of strong positive anomalies in the North Atlantic Oscillation (NAO) since positive phases of the NAO tend to be associated with above-average temperatures across northern Europe as well as strong westerly winds.

Similarly, there are strong indications that cephalopods (squid, octopus, cuttlefish) are becoming more abundant in northern Europe, possibly as a consequence of climate change and strong positive anomalies in the North Atlantic Oscillation (NAO (Hastie et al. 2009a). An increase in abundance has led to the establishment of a new fishery off the Aberdeen coast (see Hastie et al. 2009b) and has generated considerable interest among policymakers and marine ecologists. Off north-east Scotland, more boats are now trawling for squid than the region's traditional target species, such as haddock and cod. In 2010, UK squid landings exceeded 7000t (£16.8m) having risen from only 410t in 1980. Squid are highly sensitive to environmental conditions. Sea surface temperature (SST) appears to influence recruitment strength and overall distribution (Hastie et al. 2009a).

Red mullet is a non-quota species of moderate, but increasing, importance to northern European fisheries. From 1990 onwards, international landings from the English Channel and Celtic Sea region increased strongly, from zero tones in 1970 to >5038 tonnes in 2005 with French fisheries benefiting the most. Beare et al. (2004) demonstrated that red mullet are one of many species that have become significantly more prevalent in bottom trawl surveys in recent years, rising from near-absence in the North Sea during surveys between 1925 and 1990, to as many as 4 individuals per hour of trawling between 1994 and 2004.

In recent years UK and Irish fishermen have started to actively exploit populations of anchovy for the first time. Newpaper reports talk about of an "anchovy goldrush" (see figure 3) with a gradual spread of the species (as indicated by research surveys) northward into the western Channel, southern North Sea and Irish Sea over the past decade and observations of large populations of juveniles in the Thames estuary and along the Dutch coast. A recent ICES report (ICES 2008) confirmed that the species is now widely distributed over almost 80% of the North Sea, even though only occasional records of anchovy had been made off Britain and in the Skagerrak in the period between 1977 and 1989.

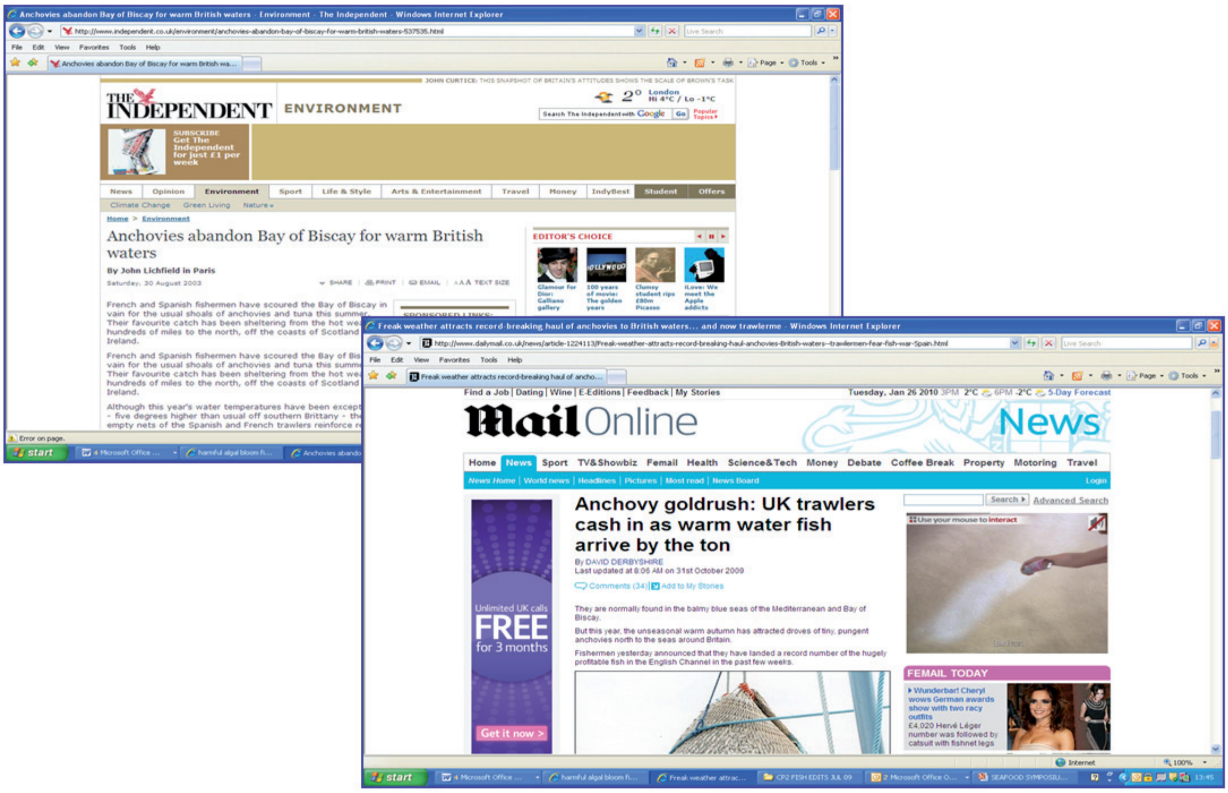

Figure 3.
Online newspaper articles from January 2010, reporting on new opportunities for anchovy fishing around the British Isles, suggested to be a consequence of recent climate change.

The effectiveness of marine protected areas

Long term climate change and shifting fish distribution patterns have been cited as a confounding factor influencing the apparent success or failure of fishery closure areas in the North Atlantic area, including the southern North Sea 'Plaice box' (see van Keeken et al., 2007). In the North Sea, juvenile plaice are typically concentrated in shallow inshore waters along the Dutch and German coast and gradually move offshore as they become larger. Surveys in the Wadden Sea have shown that 1-group plaice are now almost absent from the area where they were previously very abundant. This has been linked to changes in the productivity of the region but also to changing temperature of the southern North Sea. The 'Plaice Box' is now considered much less effective as a management measure in comparison with the situation 10 or 15 years ago and this has been attributed primarily to long-term climate change.

Marine Protected Area (MPA) boundaries may need to be 'adaptive' in the future, and yet legislative processes are rarely flexible enough to accommodate such issues. For example the EU Habitats Directive only includes an option (Article 9) to de-select unsuccessful Special Areas of Conservation (SACs) or nominate new ones, and not to amend boundaries in the light of shifting species distributions.

"The Commission, acting in accordance with the procedure laid down in Article 21, shall periodically review the contribution of Natura 2000 towards achievement of the objectives set out in Article 2 and 3. In this context, a special area of conservation may be considered for declassification where this is warranted by natural developments [climate change] *noted as a result of the surveillance provided for in Article 11".*

Another example includes fisheries closures in the Bornholm Basin of the Baltic Sea which do not account for year-to-year environmental variability and in particular the periodic inflow of water from the North Sea which greatly influences the spawning location and year class strength of species such as cod. In some years the Bornholm closure area is successful in protecting much of the cod stock, but in other years, most of the spawning population occurs outside of the boundaries of the Protected Area, and hence the MPA offers no protection at all (for a review of Baltic closure areas, see ICES 1999; 2004).

Cheung et al. (in press) provides an indication of anticipated near sea-bed temperature changes in six existing fishery closure areas mandated through the EU Common Fisheries Policy. This review suggests that most of these areas will experience a 2-3°C increase in temperature over the next 80-100 years and that the species these various MPAs are designed to protect will probability not be able to persist in the same numbers within the areas, in the future.

Recruitment/Year class strength

Fishermen and scientists have known for over 100 years that the status of fish stocks can be greatly influenced by prevailing weather conditions (Cushing 1982; Hjort 1914). Recruitment variability, also referred to as the 'year-class strength', is a key measure of the productivity of a fish stock, and is defined as the number of juvenile fish of a given age surviving from the annual egg production to be exploited by the fishery. Many authors have demonstrated strong relationships between recruitment success, fisheries catches and climatic variables in a number of key fish and shellfish stocks that are critical to the European fisheries economy, most notably cod, whiting, haddock, plaice, herring, seabass and more recently, scallops (Brander and Mohn, 2004; van der Veer & Witte 1999; Nash & Dickey-Collas 2005; and Shephard et al. 2010).

Extensive fishing may cause fish populations to be more vulnerable to short-term natural climate variability, by making such populations less able to 'buffer' against the effects of the occasional poor year classes. Conversely, long-term climate change may make stocks more vulnerable to fishing, by reducing the overall 'carrying capacity' of the stock, such that it might not be sustained at, or expected to recover to, levels observed in the past. In the NE Arctic, during recent decades, there has been a clear positive correlation between temperature and recruitment in cod, however this link was weak or non-existent in earlier periods. As pointed out by Ottersen et al. (2006), it is likely that the higher dependency nowadays of recruitment on climate, relates to changes in stock structure. Spawners were on average 10–11 years old and >90 cm long in the past, compared to an average of 7–8 years old and 80 cm long at present. This has been attributed to high fishing mortality especially from the 1960s onwards and to decreased age and size at maturation. A major implication of this is that fishery-induced impoverishment of stock structure (reduced and fewer ages, smaller sizes) can increase the sensitivity of a previously 'robust' stock to climate change.

At the northern extremes, warming tends to lead to enhancement of recruitment in cod, whilst in the North Sea, close to the southern limits of the range, warm conditions tend to lead to weaker than average year classes, and vice-versa (Drinkwater 2005). However, even though there is a demonstrable correlation between recruitment deviations of cod and temperature, this does not necessarily imply that temperature *per-se* is the causative factor behind recent poor recruitment throughout much of Northern Europe. Other aspects of the ecosystems inhabited by cod have changed in concert with temperature and these could be responsible. In particular composition of the zooplankton community on which cod larvae feed has changed significantly. The biogeographic boundary between the sub-polar and subtropical plankton communities in the northeast Atlantic have shifted northwards by approximately 1000 km since 1960, in parallel with the warming of sea surface temperature. Year-class strength is greatly influenced by the timing of spawning and the resulting match-mismatch with key prey resources (Cushing, 1990). A clear seasonal shift to earlier appearance of fish larvae has been described for southern North Sea cod (Greve *et al.* 2001; 2005), in addition it has been demonstrated that rising temperatures have coincided with marked changes in the types of zooplankton prey available to these larvae in this region (Beaugrand et al. 2002). There has generally been a decline in the abundance of the copepod *Calanus finmarchicus* but an increase in the closely related but smaller species *Calanus helgolandicus*. *C. finmarchicus* is an important prey item for cod larvae in the northern North Sea, and the loss of this key species has been suggested as a mechanism to explain recent failures in cod 'recruitment' (Beugrand 2003, 2004; Reid et al. 2001; 2003). *C. helgolandicus* occur at the wrong time of the year and are the wrong size to be of use to emerging cod-larvae. However *Calanus* (of either species) is not a major prey item for fish larvae in the southern North Sea and Baltic, and consequently several authors have argued that this 'match/mis-match' hypothesis does not provide a full explanation for recent failures in fish recruitment throughout the wider region.

Drinkwater (2005) used temperature-recruitment relationships from Planque & Frédou (1999) together with outputs from Global Circulation Models (GCMs) to predict possible responses of cod stocks throughout the North Atlantic to temperature and hydrodynamic changes. According to this study, stocks in the Celtic and Irish Sea are expected to disappear altogether by 2100, while those in the southern North Sea and Georges Bank will decline. Cod will likely spread northwards along the coasts of Greenland and Labrador, occupying larger areas of the Barents Sea, and may even extend onto some of the continental shelves of the Arctic Ocean.

Ocean acidification

In recent years ocean acidification (OA) has emerged as a high-profile and potentially very serious threat to marine ecosystem structure and function in the North Atlantic, with several authors predicting catastrophic consequences for commercial fisheries and aquaculture (e.g. Cooley & Doney 2009; Gazeau et al. 2007). The vast majority of the studies that have been published on the impacts of ocean acidification so far have tended to focus on benthic or planktonic species that are of limited importance for fisheries and aquaculture. However, it is clear that commercial species of shellfish may be impacted in the future. At high pCO_2 (low pH) the growth and shell formation of oysters and mussels seems to be impaired (Gazeau et al. 2007) and in the NW Pacific commercial oyster hatcheries are already reporting reduced survival of juveniles and hence reduced viability of aquaculture operations attributable to low pH in coastal waters.

Even though commercial fin-fishes may be less impacted by ocean acidification in terms of direct physiological effects, they may be impacted because of changes in the marine food-web. Larvae and juveniles of most fish are reliant on planktonic crustaceans which may or may not be impacted by future ocean acidification. As adults, many commercial fish species (e.g. haddock and plaice) are also reliant on bivalve molluscs or echinoderms which are predicted to decline in the future as a result of ocean acidification (Fabry *et al* 2007). Ocean acidification research programs have recently been instigated throughout the North Atlantic (e.g. FOARAM – USA, BIOACID-Germany, EPOCA-EU FP7) and it is anticipated that more information will soon emerge allowing better quantification of the financial risks associated with this problem. Based on laboratory experiments involving cod, Le Quesne et al (Cefas, 2010) demonstrated that ocean acidification might inhibit larval development and egg fertilisation success in some commercially important fish species. This, in turn, could greatly affect recruitment to fish stocks, with important consequences for long-term sustainability.

The range of opinions that have been expressed concerning possible implications of ocean acidification span from wholesale degradation of marine ecosystems (Kroeker et al., 2010, Turley et al., 2010), through to limited impact with minimal economic consequences (Hendriks et al., 2010). Very little modelling has yet taken place to scale up from laboratory experiments to populations and to consequences for fishermen and fleets (see discussion in Le Quesne and Pinnegar 2011). A preliminary economic assessment conducted by scientists at Cefas looked at the extent of possible economic losses to the UK shellfish industry (Pinnegar et al. 2012). Four of the ten most valuable marine fishery species in the UK are calcifying shellfish and the analyses suggested that losses in the mollusc fisheries alone could amount to £55-379 million per year by 2080 depending on the CO_2 emission scenario chosen. In addition another £59.8-124.6 million might be lost from the shellfish aquaculture industry assuming future CO_2 concentrations of ~740ppmv (pH 7.9-8.0).

6 Anticipated Impact on Fleets/ Economics

Gear catchability

A further means by which climate change might impact commercial fisheries includes the potential that animals will behave differently in response to the incoming gear, behaving in a more sluggish or a skittish manner (sometimes a function of temperature or light levels) and thus making them more or less vulnerable to capture (see Winger 2005 for a study on cod). In tropical tuna (the main target of Europe's distant-water fleet), strong El Niños along the west coast of the Americas, such as the 1982–1983 event, resulted in a deeper thermocline, and declines in yellowfin tuna *Thunnus albacares* catches. However, the declines were typically followed by a rapid rebound, suggesting that a strong El Niño may cause temporary horizontal and vertical displacement of the stocks that reduce their accessibility to harvesters, but with little evidence of lasting adverse impacts on population abundance (see Miller 2007). Poor catch rates during the intense 1982–1983 El Niño played a role in the migration of the US tuna fleet from the Eastern Pacific to the Western and Central Pacific. In the Indian Ocean, there are similar seasonal shifts in the location of tropical tuna schools and their accessibility to surface fishing gears. Skipjack *Katsuwonus pelamis* and yellowfin tuna tend to concentrate near the surface in areas where there is a shallow mixed layer and strong stratification, making them more vulnerable to capture. While these seasonal patterns are fairly predictable, they are nonetheless complex and variable from year to year. During the latest (and very strong) ENSO, the collapse of CPUEs in the West pushed boats to the eastern basin where very good catches were recorded following an abnormal shallowing in the depth of the thermocline induced by the ENSO event (see Miller 2007).

Dulvy et al. (2008) explored the year-by-year distributional response of the North Sea demersal fish assemblage to climate change and found that the whole North Sea fish assemblage had deepened by ~3.6 m per decade since 1981. This has important implications for fisheries since it is known that trawl gear geometry and hence 'catchability' of certain fish species can be greatly influenced by water depth (see Godø and Engås 1989, and figure 5).

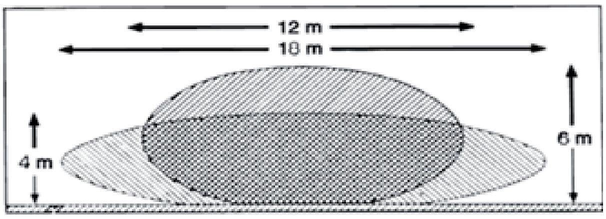

Figure 5.
Difference in trawl gear geometry at depths of 50m and 450m in the Barents Sea (adapted from Godø and Engås 1989). Headline height is typically higher (~6m) but the swept-area is narrower (~12m) when towing in deeper water, compared to tows in shallower water (4m and 18m respectively).

A further, only recently appreciated consequence of anthropogenic greenhouse gas emissions could be a change in sound transmission in the ocean (Hester et al. 2008). The relative solubility of borate and boric acid in the ocean are known to be very dependent on pH, and it is the balance of these two solutes which is thought to influence noise attenuation. As atmospheric CO_2 concentrations increase, and more of this gas dissolves in the ocean, the pH of surface waters tend to decrease (become more acidic), and this could impact sound absorption in the audible range for fishes. The decreased sound absorption will amplify ambient noise levels, and enhance long distance sound transmission. Consequently fish may be able to detect incoming fishing gear, much earlier in the future, affecting catchability.

Distant water fisheries

The EU has two types of fishing agreements with non-EU countries – fisheries partnership agreements (the EU gives financial and technical support in exchange for fishing rights) and northern agreements (joint management of shared stocks, e.g. with Norway, Iceland and the Faroe Islands). The vast majority of fisheries partnership agreements allow EU vessels to pursue migrating tuna stocks as they move along the shores of Africa (Cape Verde, Côte d' Ivoire, Gabon, Guinea, Mauritania, São Tome & Principe, Senegal) and through the Indian/Pacific Ocean (Comoros, Kiribati, Madagascar, Micronesia, Mozambique, Seychelles, Solomon Islands). However, a small number of 'mixed agreements' exist, that provide access to a wider range of fish stocks in the partner country's exclusive economic zone (e.g. in Guinea- Bissau and Morocco). As discussed in the section on 'catchability' (above), tuna distribution and migration patterns have been shown to be very sensitive to changes in ocean climate. A number of studies (e.g. Aaheim and Sygna 2000) have attempted to evaluate the potential economic impacts of climate change on tuna fisheries (including export fisheries to the EU) at various localities in the Pacific region.

The Fisheries Partnership Agreement concluded between the Community and Greenland covers the period 2007–2012 and represents an investment of 15.8 million, mainly for capelin and/or cod quotas. This fisheries agreement allows vessels from Germany, Denmark, UK, Spain and Portugal to fish in Greenland waters and is the only bilateral trade agreement concluded with a non-ACP State. As suggested by Arnason (2007), but also Cheung et al (2009b) (see discussion below), Greenland is one of the few countries where fisheries are anticipated to benefit significantly as a result of future climate change (in particular landings of cod). Consequently, it is possible that access agreements, as well as imports of fish caught by indigenous fisheries in northern countries such as Norway and Greenland, will become increasingly important to markets and consumers throughout Europe in the future. Off Greenland during the latter half of the 1990s and into the present century, cod recruitment per SSB has increased dramatically over the low values typically observed previously (Wieland et al., 2006). Since 2004 there has been inferred spawning off East Greenland and in the spring of 2007 large cod were observed spawning there for the first time in many years. This is considered a good sign, for future fisheries in West Greenland, since much of the larvae and juveniles would be expected to be transported to West Greenland by the Irminger Current (from Drinkwater 2009).

Recreational fisheries

A number of fish species that are heavily targeted by the recreational fishing sector throughout Europe are also anticipated to be impacted by future climate change. For example biomass estimates for seabass in the Western English Channel have quadrupled from around 500 t in 1985, to in excess of 2100 t in 2004/2005, with populations also increasing in the Eastern Channel, North and Irish Seas (Pawson et al. 2007). This has resulted in an expansion of seabass fisheries, both within the commercial fisheries sector, but also in the recreational fishing sector, for which seabass is a key target species.

Many recreational fishermen target salmon along the coasts. Salmon depend on environmental variables as migratory cues (Friedland et al., 2003). It has been argued that few North Atlantic fish species will be as intensely affected by climate change as Atlantic salmon (Ottersen et al., 2004; Jonsson & Jonsson 2009). Whalen et al. (1999) reported that peak migration of salmon occurs later in spring for tributaries with lower temperature. Also, annual variation in the timing of peak migration of Atlantic salmon is related to variation in annual water temperatures (McCormick et al., 1998). Changes in precipitation patterns under future climate change scenarios, may influence the ability of smolts to successfully migrate from rivers to the sea. Conversely, low water flow in rivers can have a negative effect on upstream migration of adult salmon returning from the sea to rivers to spawn (Solomon & Sambrook, 2004). Studying radio tagged salmon in four south western rivers in England, Solomon & Sambrook (2004) noted that when water flows were relatively high, the majority of migrating adult salmon passed through estuaries and into the rivers with a minimum of delay. However, when river flow was low (drought years), most fish arriving from the sea did not pass quickly into freshwater but remained in the estuary or returned to sea for several months. Many fish subsequently failed to enter the river even when favourable flow conditions returned, possibly as a result of lost physiological opportunity (Solomon & Sambrook, 2004). Jonsson & Jonsson (2009) provided a detailed review of the likely effects of climate change on salmon and seatrout, with particular reference to water temperature and river flow. The authors show that climate change will likely impact upon embryonic development, hatching, emergence and growth (both in the sea and in rivers). They also highlight the potential for increased virulence of some diseases as temperatures become warmer.

Changes in the economics of fishing

As climate change is projected to affect both the quantity and quality of marine fish caught by fleets as well as the distribution or allocation of resources within and between nations' Exclusive Economic Zones (EEZs), the economics of fishing will also be significantly affected. However the true economic impact of climate change will depend on how the market and consumer respond to such changes, with fish protein typically traded as a global commodity and prices set by gobal markets rather than reflecting local availability.

Merino *et al*. (2010) used a modelling approach to study the production-consumption of small pelagic fisheries that supply fishmeal for aquaculture. They demonstrate that regional stocks are able to cope with both climate variability and climate perturbations except when these climate impacts occur in synchrony with an expansion of international market demand, and a sub-optimal management scheme (Merino *et al*. 2010). When this modelling approach is applied to make future projections under scenarios of climate change, Merino *et al*. (2010)

suggest that the sustainability of small pelagic fish resources at a global level, even in the face of climate change, depends more on how society responds to climate impacts than on the magnitude of climate impacts *per se*.

Similarly, Arnason (2007) used an economic model to project potential economic impacts of climate change on fisheries and on the national economies of Iceland and Greenland. The dramatic increase in fisheries yield assumed for Iceland resulted in only miniscule increases in national GDP, despite the fishing industry accounting for around 10% of GDP and 40% of export earnings in Iceland. The accumulative impact of climatic warming on Icelandic GDP was only 4% by 2054, and given economic volatility and measurement errors, this level of economic growth is considered hardly detectable at the 95% significance level. Benefits for the national economy of Greenland were greater (a 40% increase in GDP by 2054) but this assumed an enormous increase the fish stock (by 200%) and it should be remembered that the fishing industry in Greenland is the main source of non-government employment and local economic activity (over 90% of all exports). This highlights the importance of understanding human and societal responses in assessing climate change impacts on fisheries and marine systems.

While fisheries are in the process of adapting to the changes in fish stocks and ecosystems, the cost of fishing operations may temporarily increase. In the past, fishing sectors have adapted to altered environmental conditions or reduced stock levels by switching target species, changing gear type (Grafton 2010), and/or by moving to new areas. However, such changes in fishing tactics have direct and indirect implications for the cost of fishing. For example, earnings in the European sardine fishery were estimated to decrease by up to 1.4% on average per year with rising temperatures (Garza-Gil et al. 2011). Capital costs, i.e., the cost of vessels, fishing gear, processing plants, etc., would all be affected by climate change (Allison et al. 2009). In addition, changes in migratory routes and fish distribution would affect travel time which can lead to significant increases or decreases in fuel costs and the cost of ice. A recent study by Abernethy et al (2010) demonstrated that fuel costs can be a very important determinant of fleet behaviour, with fishing vessels tending to operate closer to port when fuel costs are high. This suggests that 'adaptive capacity' may be limited in some fleets and it is possible that some fishermen may choose to leave the industry rather than follow their traditional target species northwards (see discussion in Tidd et al 2011). A profitable fishery attracts additional effort (vessels enter), eventually leading to overcapacity and less profit. Similarly, fishing vessels exit depending on their declining economic viability. The finescale balance between costs and revenues can be key to whether or not European fisheries are able to adapt to future climate change.

Adapting fisheries for the future

There are a number of studies that investigate the vulnerability and adaptive capacity of the fisheries sector world-wide to climate change at a global scale (Allison et al. 2009; McClanahan et al. 2008). However, until recently there has been little directed analysis at the local scale of how climate variability and change will affect the lives and livelihoods of those involved in the European fishing and fish processing sectors. A recent review paper by Badjeck et al. (2010) attempted identify the main pathways through which climate variability and change can impact upon fishing-dependent communities. The authors of this study point out that most research so far has tended to look at climate-driven changes in ocean productivity and have not considered indirect effects such as the fact that extreme weather events may disrupt fishing operations and/or land-based infrastructure. Storms and severe weather events can destroy landing sites, boats and fishing gear (Westlund et al. 2007). For instance, during Hurricane Gilbert in 1988, Jamaican fisherfolk lost 90% of their fish traps resulting in a huge loss of revenue and high cost of repairs, as well as resulting in the inability to resume fishing activities promptly after the disturbance (Aiken et al. 1992).

Fishery resources will be more robust to climate change if the compounding stresses from overfishing, habitat degradation, pollution runoff, land-use transformation, competing aquatic resource uses and other anthropogenic factors are minimized. Paradoxically, this could be largely achieved not through the pursuit new biophysical research, but by developing and applying social institutions and mechanisms for achieving effective adaptive management. In this context fisheries that have been successfully managed to achieve resource sustainability will probably be much better positioned to respond to the vagaries of climate change than those whose governance has been more *laissez faire* in nature. Fisheries in the latter case will probably have to respond much more reactively to disruptive changes resulting from climate change, compared to those in the former category which would seemingly be better prepared to confront such challenges.

Sumaila and Cheung (writing in a report for the World Bank) attempted to establish the costs of adaptation to climate change in the fisheries sector worldwide. The analysis began by detailing the likely impact of climate change on the productivity of marine fisheries (more than 1,000 species) and, through that, on landed catch values and household incomes. Adaptation costs were then estimated, based on the costs of restoring these revenue indicators to levels that would have prevailed in the absence of climate change. The impact of climate change on marine fisheries was assumed to primarily occur through changes in primary productivity, shifts in species distribution and through acidification of the oceans. The authors considered three scenarios that reflect these impacts. Climate change was predicted to lead to losses in gross fisheries revenues world-wide of $10–31 billion by 2050. Governments have implemented various measures to manage fisheries, both to conserve fish stocks and to help communities that depend on fishery resources adapt to changes caused by overfishing and other factors. Measures include buybacks, transferable quotas, and investments in alternative sources of employment and income. Adaptation to climate change is likely to involve an extension of such policies, with a focus on providing alternative sources of income in fishing communities to lessen the dependence on fishery resources. In Europe the estimated annual cost of adaptation was between 0.03 and 0.15 $ billion per annum.

7 Knowledge gaps and key recommendations

In order to draft a list of knowledge gaps and priority research areas within the context of fisheries and climate change, participants at the EFARO fisheries workshop (in February 2011) reviewed the briefing documents provided and listed scientific topics that they judged would benefit from future research, and which would yield important insights of relevance to EFARO, European policy makers and fishery stakeholders. 26 separate knowledge gaps were identified and each of these is discussed below, (following further clarification by workshop participants). A simple scoring exercise has been carried out on the basis of urgency/immediacy and relevance. Research themes were also categorised according to perceived 'value for money', and their match/relevance to the stated objectives and remit of EFARO (i.e. to promote scientific cooperation in the area of fisheries and aquaculture specifically) (see Appendix I).
Each 'knowledge gap' is accompanied by a recommendation describing the research required and an additional column was added to the table in Annex I, providing insight into the perceived maturity of the knowledge base in each case. For example studies linking fish recruitment to climate have been conducted for more than 50 years and this topic has scored '5', whereas detailed studies on ocean acidification have only been carried out within the past 5-10 years and this topic has been scored '1'.
When attempting to prioritise the research gaps that need to be addressed, a useful approach is to look for those that score highly in terms of immediacy, value for money and relevance, and compare this score with the maturity of the knowledge base, such that those that offer the highest overall score in terms of importance and the lowest in terms of current knowledge should be particularly prioritised. A good example of this is knowledge gap "3A" *Modelling the behaviour of fishers.*

Theme 1 – Modelling & Monitoring the Physical Environment

1A - Improved Regional Climate Models (RCMs)

Although substantial efforts have been made to predict and assess the effects of atmospheric climate change for the next century (mainly coordinated through the IPCC), comparatively little has been done so far to do the same for marine ecosystems. There is an urgent need to develop better coupled ocean-atmosphere regional models to forecast physical conditions in the sea at the horizontal and vertical scales required to quantitatively assess possible future ecosystem changes, especially changes in fish populations. This requires improved methods of downscaling from the global atmosphere-ocean Global Circulation Models (GCMs), also probabilistic ensemble runs using multiple models and climate forcing scenarios in order to provide insight into uncertainty and robustness .

Recommendation - Regional ocean-atmosphere models shoud be developed to cover all EU marine areas to assess possible future ecosystem changes. A consortium of modeling institutions to share knowledge, experience and methods on regional modelling and downscaling should be established.

1B - Improved Global Circulation Models (GCMs)

Improvements in GCMs are required before the regional climate models (and hence predictions about impacts) will better reflect reality. This will be achieved through increased horizontal and vertical resolution of the atmosphere-ocean GCMs and incorporating small scale processes such as upwelling zones, that are not currently well represented in today's models. Improved models of future wind strength and direction, plus storm tracks are needed as present projections differ greatly between GCMs and in many areas it is unclear whether conditions will become stormier or less stormy. This knowledge is required to determine future primary production levels and help determine feeding success of fish larvae. Wind and storms also affect fisheries directly through their impacts on maritime safety and the ability of fishing vessels to fish (i.e. how many lost days there are) as well as fuel efficiency and thus net revenues.

Recommendation - Higher resolution Global Circulation Models (GCMs), with particular attention to improving feedback mechanisms and wind fields need to be developed.

1C – Long-term datasets for climatic monitoring and model validation

Long-term datasets of physical parameters such as temperature and salinity (but also biological indicators such as chlorophyll concentrations or nutrients) are needed to validate climate models (to keep them 'true') and also to help determine whether observed changes in biology (e.g. recruitment patterns) and/or fish catches are primarily attributable to variability in the physical environment (climate change) or other anthropogenic drivers. For several regions of Europe high-quality long-term seawater datasets exist from coastal monitoring stations or offshore vessels, some of which have been in operation for more than 100 years (see MacKenzie and Schiedek 2007). However in other areas records are far more sporadic, and oceanographic time series need to be reconstructed using whatever piecemeal information exists (e.g. from vessel weather logs or climate proxies). It is known that previously unutilised data exists in paper archives throughout Europe and further effort is required to recover, digitise and make such information available. Similarly, very little effort has been dedicated towards the development of maritime climate proxies (such as those based on sediment cores or mollusc growth rings) that might offer insight into climatic change and/or fish populations in the sea over much longer time scales (for example records of fish scales recovered from sediment cores; see Baumgartner et al 1992).

Recommendation – Data from archival sources should be mined to recover maritime climate dataNumerical techniques to reconstruct useful time series should be developed. Where possible locally-relevant long-term marine climate proxies should be established, especially where these might provide insight into associated long-term patterns of fish abundance and recruitment,

1D – Better understanding of low oxygen events and their consequences

Dissolved oxygen is a fundamental component of water quality and is vital to life in the seas, with its presence or absence regulating virtually all biological and chemical processes. Despite this we know surprisingly little about spatial patterns of dissolved oxygen across European seas, how oxygen levels vary seasonally and on an inter-annual basis. Hypoxia (low oxygen) is starting to emerge as an issue of major concern, however, little is understood with regard to the possible impact of low oxygen zones on fish and fisheries. In the central North Sea an area known as the 'Oyster Grounds' (part of the Dogger Bank) has witnessed decreasing oxygen levels in recent years and hypoxia has been reported for coastal waters around the German Bight and within the Baltic. Low oxygen is predicted to occur more regularly in the future as a result of climate change. Waters will be warmer by 2–3°C and therefore contain less dissolved oxygen by 0.4 mg l-1.

Recommendation – In order to understand the dynamics of oxygen within the context of long-term climate changemapping and monitoring of oxygen levels in the environment should be implemented. Laboratory experiments and development of telemetry techniques are needed to determine the sensitivity of fish life stages to low oxygen, or the avoidance of low oxygen areas by fish in the wild.

1E – Catchment to coast issues

Changes in riverine discharge rates can affect coastal water quality e.g. salinity, turbidity, nutrient loading, oxygen and temperatures with a commensurate impact on the carrying capacity of coastal fish communities as well as the transport and uptake of pollutants or heavy metals. These impacts will be greatest in closed or semi-closed waters and/or where there is limited water exchange. To date we have very limited understanding of the influences that river catchment processes might have on marine fish communities, although it is known that flatfish in coastal waters can derive a considerable portion of their diet from sources that are ultimately a result of riverine inputs (e.g. Darnaude et al. 2004). Whether or not changes in precipitation patterns and therefore riverine flow rates will have significant consequences for marine fish food-webs is an area requiring additional research. Inshore and coastal areas include known nursery grounds for many marine organisms, including fisheries target species (such as seabass). Estuaries and coasts are also important for diadromous species such as salmon and eels. These 'diadromous' species are thought to be particularly vulnerable to climate change (see Lassalle & Rochard 2009; Jonsson & Jonsson 2009), with impacts both in the freshwater and maritime phase.

Recommendation – Research on the impacts on primary productivity and links to higher trophic levels, including marine and diadromus fish of freshwater inputs and nutrient changes in the coastal environment are required.

Theme 2 – Understanding the ecological consequences of climate change

2A- Evolutionary adaptation to changed climatic conditions

The impact of climate change on marine fishes and invertebrates will be dependent on how well these organisms adapt through evolution, and altering their behaviour or physiology. Such adaptive responses can be genetic or phenotypic. For example, a fish species may be able adapt to ocean warming by a shift in their physiological temperature preference/tolerance. Natural selection may favour particular genetic traits (e.g. climate sensitive hemoglobin polymorphisms; Petersen & Steffensen 2002) and if these genes offer an advantage in terms of breeding success or lower mortality, then they will rapidly spread within the wild population. Different species may have different adaptive capacity, and thus responses to climate and ocean changes (such as a lowering of pH). In addition, species adaptability may vary under multiple-drivers of biological and ecological changes e.g. fishing or pollution. Thus, improved knowledge on species adaptability will improve understanding and predictability of responses. This is essential to develop effective and sustainable fisheries management measures in the future.

Recommendation – Assess the adaptive capacity of marine species to changes in ocean conditions, specifically temperature, ocean chemistry (e.g. acidity and oxygen) in order to develop sustainable fisheries straetegies.

2B – Understanding and modelling fish behaviour

Fish may exhibit a variety of behavioral responses when faced with environmental conditions that they perceive as being sub-optimal. This can include spatial movements, shifts in migration routes (and/or timing), relocating to new spawning sites, swimming at different levels of the water column or retreating to greater depths which usually remain cooler. Such reactions to external stimuli are inherent characteristics of the behavior of fish species. Horizontal and vertical movements and migrations occur at various time scales from daily to seasonal, and yet we know very little about the motivation behind some of the behavioural changes that have been observed so far, or insight into how such factors will likely change in the future. Understanding the motivation of fish to move within their available range, for example in order to maximize growth or minimize mortality, will allow better prediction of possible fishery changes (e.g. changes in catchability) that might occur as a result of long-term climate change. Available techniques to study such issues include the application of individual-based models incorporating behavioural rules, but also advanced telemetry techniques such as the data storage or satellite tags that record location, depth, acceleration and orientation as well as a suite of determining environmental variables.

Recommendation – Prediction of changes to migration patterns for pelagic and demersal fish species bymaking use of electronic tagging technologies but also biomarkers such as stable isotopes, parasites, genetics, etc. to advise on anticipated future fishery changes

2C - Scaling up from ocean acidification lab experiments to populations & ecosystems

Currently, claims regarding the potential implications of ocean acidification range from catastrophic ecosystem collapse to negligible impact on most biota. Consequently there is considerable confusion with regard to understanding whether or not commercial fisheries and aquaculture will be impacted by ocean acidification in the future and in particular there has been little effort to try to 'scale up' from the rapidly expanding number of short-term laboratory experiments to understanding implications at the population or ecosystem scale. It is only by developing such methodologies will we be able to predict the long-term economic risks posed by ocean acidification, and the need for action to mitigate such problems. There is an urgent need for pragmatic, well-reasoned and holistic advice, to be followed by more detailed individual-based modelling as knowledge increases.

Recommendation – Investigate the sensitivity of ecosystems to ocean acidification using current single-species and ecosystem modelling frameworks, taking into account anticipated changes in organism physiology (calcification, recruitment, scope for growth etc.) and their overall consequences for yield.

2D – Understanding & predicting changing species interactions

Although methodologies have developed to predict changes in the distribution of species in response to climate change (e.g. bioclimate envelope models; Cheung et al. 2009a), so far there has been very little attention on possible implications for species interactions, for example spatial overlap between predators-and prey. It can be incredibly difficult to predict with certainty how food-webs might be disrupted by new species arriving or a key predator/prey departing or declining. Complex modelling techniques are required to address such issues, but this necessitates improved understanding and data to parameterise such models. The arrival/departure of species may also impact fisheries selectivity and discard patterns (technical interactions). Existing fishing fleets may capture newly arriving species that appear on traditional fishing grounds, whereas migrating fisheries (following traditional target species) may catch other species of conservation concern that are not the main target as they move. Studies aiming to investigate changing species interactions will need to consider the whole life cycle of each species, since there may be phases that are particularly vulnerable to a match or mismatch with prey and predator resources. Studies will need to consider issues such as density dependence and cannibalism as well as changes in disease transmission and overall consumption rate (which will usually increase at warmer temperatures).

Recommendation – There is a need for surveillance and monitoring programmes to enable modelling of changing distribution patterns in response to climate. Improved data on interaction dynamics (e.g. long-term stomach content datasets) and continued development of ecosystem and multispecies modelling techniques are needed to enhance fishery advice.

2E - Fisheries in the Arctic

Model projections of future climate suggest that the some of the largest changes are expected to occur in the Arctic with increased temperatures and the disappearance of sea ice, at least during summer months. This will result in higher primary production and hence higher fish production overall, although it is unclear whether this will primarily be species of commercial interest. Several authors have predicted enhanced yields for fisheries in Greenland, Iceland and Norway (e.g. Arnason 2007) and that this will benefit the economies in these countries. Another aspect that has been little discussed is increased probability of the mixing of Atlantic and Pacific stocks, such as capelin, cod and Pollock. Already there is evidence that several Pacific species have traversed the ice-free channels of the Arctic including a Grey Whale (Scheinin et al. 2011) and pink salmon. What this new mixing of populations might mean in terms of ecosystems and genetic population structure remain unclear, although the topic clearly warrants further investigation.

Recommendation – Studies are required to establish the conditions under which commercial fish species will enter the Arctic and the probability that they will establish viable populations once there. Based on these results, the probability of Atlantic and Pacific stocks mixing needs to be examined and future insight is needed into what this might mean for fisheries management.

2F - The spread of non-native/invasive species

Climate change and increasing water temperatures are expanding or otherwise altering the distribution of many marine species, sometimes providing opportunities for commercial exploitation in the new areas, e.g. seabass, red mullet, john dory, anchovy and squid, but also the expansion and establishment of non-native species that may cause actual or potential harm to indigenous species, commercial fisheries and coastal economies (see fig 7). Climate change may increase the survivability of non-indigenous species transported with ballast waters, especially when favourable conditions occur at the point of discharge. Some non-native marine species such as the Pacific Oyster that are known to have expanded their range in recent years, can support important fisheries but were initially introduced under the explicit understanding that temperatures were too cold to allow reproduction (Utting and Spencer 1992). Our ability to predict and monitor changing distributions of particular species remains limited and requires further research investment. Some attempts have been made to predict the available habitat (in terms of temperature) of incoming species now and in the future, but this work is at a very preliminary stage (e.g. Herborg et al. 2007).

Recommendation – Studies are needed that predict future distribution patterns of introduced non-native species, especially those that pose a threat to commercial and recreational fisheries. Particular attention should be paid to bioclimate envelope models that explicitly incorporate climatic processes in order to provide projections of suitable habitat and likely range expansion.

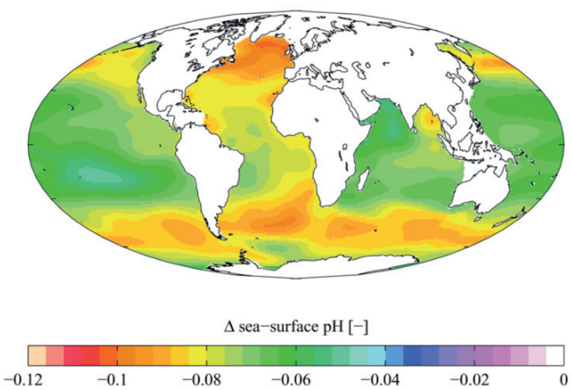

Figure 6.
Potential mixing of previously isolated capelin stocks as a result of ice-free conditions in the Arctic. (Fisheries and Climate Change-EFARO GA, Göteborg 27 May 2009)

Figure 7.
An example of a non-native species that has expanded as a consequence of rising temperatures and have posed a significant threat to indigenous species, European fisheries and coastal economies Pacific Oyster (Crassostrea gigas, Oscar Bos IMARES)

2G - Biological/ecological data recovery

Climate-related changes in ecosystems and fisheries often resolve themselves at multi-decadal timescales. Therefore, the recovery of historic data series that span multiple decades for fish populations can yield very useful insights into long-term changes that are not apparent over shorter time periods. Such data can include biological information, for example on size-at-age, maturity status, spawning times or stomach contents, but also the volume and spatial distribution of catches which can be used to reconstruct shifts in fish distribution or productivity (e.g. Engelhard et al. 2011). Archived materials such as fish otoliths can reveal changes in temperature-related growth rates or thermal stress in key commercial species (e.g. Pilling et al. 2007), and/or the timing of key life history events such as spawning or settlement. Often it is considerably less expensive and more insightful to recover historic data and extend time series back in time, than to collect a single year of new data. Therefore such research projects can represent good value for the limited financial resources required.

Recommendation – Recover fishery-related data from logbooks, archives, etc. that span multiple decades for fish populations, and will yield very useful insights into long-term changes at relatively low cost.

2H - Ecosystem productivity and carrying capacity

The underlying carrying capacity and productivity of marine ecosystems directly affect targets and reference points in fisheries management. Fisheries management currently focuses strongly on achieving Maximum Sustainable Yield (MSY), which is the level of catches that can be sustained without irrevocably damaging the stock and causing the population to collapse. This is expected to vary under climate change and increased climate variability, i.e. MSY is a 'moving target'. Climate and ocean changes can affect the productivity of stocks through changes in recruitment and interactions with other species, such as the match or mismatch with key zooplankton species on which fish larvae feed. Different stocks (targeted and non-targeted) are likely to be affected in different ways, depending on their particular life history characteristics. MSY targets and limits may need to be adjusted downward or have room for increase under climate change; however, existing fisheries assessments do not explicitly consider these factors and our understanding of the implications of such factors is limited.

Recommendation – Development of assessment models and reference point/targets for integrated ecosystem assessment and management that explicitly incorporate climate and ocean change effects. Management Strategy Evaluation to test for the adaptability of existing management measures to climate change and exploration of alternative management strategies that are adaptive to climate change.

2I - Understanding recruitment uncertainty

Recruitment may be defined as the number of fish of a given age class surviving from the annual egg production to be exploited by the fishery. Classic stock–recruitment models often explain only a small fraction of the inter-annual variation in recruitment and a considerable body of research over the past 50 years has focused on the derivation of new recruitment models that better characterize variability on the basis of environmental or climatic indicators. For many fish and shellfish stocks across Europe clear correlations have been demonstrated between recruitment and seawater temperature or the North Atlantic Oscillation (NAO). On the basis of such relationships, there have been attempts to predict recruitment into the future using using outputs from regional climate models (see Drinkwater 2005; Kell et al. 2005). Population models are particularly sensitive to assumptions regarding recruitment and yet, despite the many years of study, there is still considerable uncertainty and such relationships have rarely been used in operational stock-assessment modelling. Further research is required including models that explicitly consider changes in ocean currents and fluxes, as well as models that consider links with other trophic levels such as key prey resources.

Recommendation – Process based modelling studies are required linking outputs from regional climate models (that replicate currents, fronts, prey fields etc.) with survivorship of eggs and larvae, and thereby year-class-strength.

Theme 3 – Understanding the response of fleets and fishers

3A - Modelling the behaviour of fishers

Fishermen and fleets may respond to the effects climate change in a number of different ways, depending on how the effects manifest themselves on underlying fish populations and thus on potential revenues and costs within the industry. In recent years social scientists, working together with fisheries researchers have developed a number of approaches to predict how vessel owners and fishermen might react to changing circumstances (for example Hutton et al. 2005; Tidd et al. 2011), whether this results from the imposition of new spatial closure areas, rising fuel costs or changes in the availability of particular species. However, comparatively little attention has been dedicated towards understanding the future impacts of climate change specifically and this is partly due to difficulties in predicting/projecting key non-climatic determinants of fishery behaviour including prices, fuel costs, demand for fish etc., all of which will impact the 'adaptive capacity' of the industry to future climate change. Fisher behaviour is impacted by many different factors, including location and availability of target fish stocks, price of fish products, distance to port, market demand for fish, fuel costs, management strategies and future perceptions. Where vessel monitoring system (VMS) data are available, it might be possible to predict spatial fishing patterns and how they will alter in response to climate change, as well as the factors that determine when a vessel will 'enter' or 'exit' the fishery.

Recommendation – Improve understanding of social and economic drivers of fishing and stakeholder responses under different climate change scenarios.

3B – Adaptive capacity in fishing communities

Fisheries managers and fishermen themselves have historically had to adapt to the vagaries of weather and climate. Uncertainty is inherent in fisheries, so there is an expectation of change and experience of coping with and adapting to it. However adaptive capacity can vary substantially and may be dependent on a wide diversity of sociological and economic factors, many of which are poorly understood, including: demography of the fishermen themselves and their willingness to accept change (new gear, fishing locations, target species etc.), ties to particular landing ports or locations along the coast, financial commitments (e.g. loans and mortgages). Not all fishermen or fishing companies have the 'adaptive capacity' and flexibility necessary to exploit new opportunities or to minimise financial losses in the face of climate change. For example it might be impossible for certain operators to afford the new gear or processing facilities necessary to target/access an incoming species and thus they will be out-competed by other operators.

Recommendation – Baseline social-science research is needed to inform policy makers with regard to the 'adaptive capacity' of fleets and fishermen to future challenges and changes, and to predict potential 'winners' and 'losers' under future climate change scenarios.

3C - Impacts of climate change on recreational fisheries

In recent years the profile of recreational fisheries within Europe has risen appreciably and this sector is now being brought into the general framework of the Common Fisheries Policy and the EU Data Collection Regulations. The importance of recreational fishing in terms of social welfare and economic value should not be underestimated, but until recently this sector has suffered from a lack of monitoring and surveillance data as well as attention from researchers and social scientists. Recreational sea fisheries across Europe are incredibly diverse and encompass a wide range of activities including angling, coastal netting and spear fishing. Consequently it has proven very difficult to collect representative statistics on the sector, and to judge the motivation of those citizens involved. The motivation of recreational fishers rarely focuses on profits, and can encompass many different aspects of 'quality of life', therefore it can be difficult to predict how recreational fishers might respond to future climate change. Within the context of climate change, target species may move to other locations, change migration routes or disappear altogether, sometimes resulting in conflicts between recreational fishing activities and commercial fishing for the remaining resources. At the same time new species of recreational interest (e.g. seabass) may arrive offering new opportunities and encouraging more citizens to engage in the activity.

Recommendation – Research is required to determine how changes in climate will harm (or benefit) recreational fisheries economically and socially. Also research is needed to identify and/or develop appropriate adaptive management strategies for the recreational fishing sector.

3D - Adaptability of international fisheries management

Access to fisheries resources by commercial fishing fleets is largely regulated through agreements based on political boundaries such as Exclusive Economic Zones (EEZs). Since resource distribution is expected to shift under future climate change, there will be gains and losses as species move from one political jurisdiction to another. This will create tensions between countries that share resources, particularly for straddling and migratory stocks. There is a clear need to study whether or not existing international legislation and agreements are sufficiently flexible to accommodate and resolve these issues. Research and surveillance is needed in order to predict in advance when such conflicts might arise, to determine future trajectories and to find amicable solutions to resource allocation issues. This will necessitate a combination of physical-biological modelling as well as development of techniques for conflict resolution.

Recommendation – Models of future fish distribution and fishery behaviour (recommendation 3A) are required in order to pre-empt conflicts associated with changes in resource distribution and access rights. Social science research into conflict resolution tools might also be useful in this context.

3E - Catchability of fish in response to fishing gear

It is clear that changes in the behaviour of fish will impact upon the vulnerability of species to certain fishing gears (i.e. 'catchability') and consequently catch-per-unit-effort. To date the knowledge-base with regard to understanding and predicting such effects is somewhat piecemeal and largely anecdotal. While greater understanding would be beneficial (for example to establish whether or not more or less precautionary management measures might be needed in the future), it is apparent that autonomous adaptation within the fishing industry will continue to act in such a way that fleets will adapt and respond rapidly to changing circumstances and do not, therefore need the explicit assistance of the research community. A potentially more significant issue for research concerns the possibility that fishery-independent survey programmes will no longer provide a truly representative or consistent picture of population status, and may need to be revised/revisited in the future.

Recommendation – Determine whether changes in environmental factors such as temperature and pH are likely to lead to sampling efficiency changes that affect survey gears and data collection programmes.

Theme 4 – Understanding the wider maritime economy

4A - Global Economics and Trade

It is anticipated that climate change and ocean acidification will not only impact fleets and fishermen within Europe but will have significant consequences for fish production the world over. Fish and seafood are globally traded commodities. Countries that traditionally export seafood products to Europe will likely face shortages of fish protein in the future (see Cheung et al. 2010a), or increased internal demand in the face of falling agricultural yields on land. Consequently trade flows will undoubtedly change in the future and this will affect prices and markets. Already climate variability in the Pacific is known to have a significant impact on the price of fishmeal in the North Sea (Merino et al. 2010). A more thorough assessment of global fisheries economics is needed in order to provide the context for detailed local studies on fisheries responses to climate change.

Recommendation – Development of a general equilibrium model approach to determine more precisely the implications of climate change for patterns of supply, demand and prices in the international trade of fish products.

4B - Carbon budgets (emissions from fishing vessels, natural sources & sinks)

Carbon emissions from ships and fishing vessels are currently excluded from international climate change mitigation commitments such as the Kyoto protocol. However, it is known that fishing vessels that operate certain gears (e.g. beam trawls) release a disproportionably large quantity of greenhouse gasses, whereas others are more fuel-efficient and there is a growing move towards introducing limits and restrictions on shipping emissions in line with those imposed on other forms of transport. At present there is very limited understanding of the contribution that fishing makes towards global carbon emission budgets/schedules. However, in recent years the EU Data Collection Regulations (concerning fisheries) have been amended so that signatories are required to report kilowatt hours and fuel efficiency among their respective fishing fleets. A more difficult issue to address, concerns the potential impact that fishing might have on natural sources and sinks of carbon in the ocean. Already, lobby groups and conservation bodies have suggested that one additional benefit of creating marine protected areas or fishery no-take zones, might be increased uptake and retention of anthropogenic carbon, but this is based on very limited evidence concerning magnitudes and rates.

Recommendation – Research on the aggregate impact on carbon turnover/retention in benthic habitats, and the possible impact of disturbance of such processes by fishing gears. Collation of information concerning the contribution that EU fishing fleets make towards global carbon emission budgets.

4C – Models that consider multiple anthropogenic stress factors

The release of greenhouse gasses and the resulting impact on global climate is only one way that humans can affect processes in the seas and oceans. Humans may also impact marine ecosystems directly through intensive fishing, release of contaminants and nutrients, as well as habitat modification (e.g. offshore construction or dredging). Models are crucial to the testing of different management options in a multi-sectoral context. In recent years a number of highly-complex, integrated model frameworks have evolved. These models include a wide range of architectures, from simple data-driven models to highly complex mechanistic 'end-to-end' models that attempt to replicate all processes linking physics through to fisheries and regional economies. Complex modelling frameworks have been used to investigate the implications of 'bottom up' climate forcing on lower tropic levels, as well as 'top down' processes that affect fish populations and higher trophic levels (e.g. fishing). This structure allows changes to propagate through the ecosystem, to test available hypothesis of fisheries and ecosystem dynamics, and ultimately to provide a comprehensive view of the outcomes of combined climate and human effects on the ecosystem. However, complex ecosystem models are typically very data demanding and their outcomes may be difficult to interpret and communicate.

Recommendation – Develop risk assessment and decision-making tools using integrated ecosystem models that include climatic, ecological and socio-economic knowledge.

4D – Trade-offs between fisheries, conservation and other human activities

The need to consider various non-fishery management objectives (e.g. conservation of marine biodiversity, development of marine renewable energy) alongside fishery management targets is inherent in the ecosystem-based approach to fisheries management. Climate change alters the biology, ecology and distribution of marine species. This in turn may affect the spatial overlap between target and non target species, particularly those that are vulnerable to fishing e.g., sharks and rays; thus increasing/decreasing the catchability of vulnerable bycatch species, many of which are subject to statutory protection. In addition, changes in ocean conditions may affect the distribution of species such that they occur more commonly in areas dominated by other human activities such as offshore windfarms or oil and gas exploration zones, and are thus inaccessible to fisheries. Currently, very little research has been carried out looking at multiple users of the marine environment, and whether or not fisheries, conservation and other objectives can be achieved simultaneously in the light of future climate change.

Recommendation – Application and development of multi-sector modelling approaches (see recommendation 4C) as well as predictive assessments of future distribution patterns and fleet-behaviour models (recommendation 3A) that take into account other spatial users.

4E - Data recovery - socio-economic

Historic social and economic data on the fishing industry are key to developing realistic scenarios with which to predict the likely prospects of fisheries in the future. Changes in past prices and costs can be considered within the context of observed environmental variability to look for significant and persistent relationships that might hold given long-term climate change. Such datasets are often difficult to assemble and require significant expertise, especially prior to the publication of the first Annual Economic Report for European fishing fleets in 2002. To date, the collation of long-term social and economic datasets specifically concerning fisheries has been largely neglected, as has the development of appropriate econometric techniques to analyse such datasets. In 2010 modelling work was published focussing on the global fish meal market, including the importance of sandeel resources in the North Sea and the influence of world-wide climate variability (Merino et al. 2010). However further work is needed to develop 'response functions' that offer useful insight into climate change responses in other European fisheries the future. These data are important for designing climate change adaptation strategies for fisheries.

Recommendation – Development of regional databases of social and economic data (including fish and fuel prices, costs and revenues). Research into 'response functions' based on econometric data, that relate fishery productivity and development to environmental and climate-related indices.

4F – Aquaculture, fisheries and climate change

This position paper does not consider the impact of climate change on marine aquaculture in any great detail, since the topic would warrant a position paper of its own, with specific research needs and knowledge gaps highlighted (e.g. see Callaway et al. in press). However, fisheries and aquaculture do interact in terms of both supplying fish protein to global fish markets and therefore influencing prices, and through industrial capture fisheries that are required to supply fish meal and oil to the aquature sector. These fisheries are typically very sensitive to climate variability and more research is needed, concerning the interactions and inter-dependencies between these two maritime industries. Long-term climate change, as well ocean acidification will impact the types of fish or shellfish that can be maintained or reared in a particular water body. New aquaculture facilities are being developed to take advantage of changing environmental conditions, with warmer water species such as seabass and gilthead seabream being reared in more northerly waters than was feasible in the past (e.g. in the Bay of Biscay). Furthermore, an additional indirect driver of mariculture development associated with climate change (mitigation) concerns the rapid development of offshore renewables such as wind-farms that are suggested as potential anchor sites for cages and nets, or as sites to lay out shellfish. Increasing temperatures may change the incidence and types of diseases among farmed species and the treatments required to protect the farmed stock. Effluent, from fish and food waste will probably decompose at different rates in higher temperatures. All of these issues exacerbated by climate change could potentially impact wild populations of the same species and/or other ecosystem components.

Recommendation – An analysis of optimum conditions for key mariculture species should be carried out in parallel with 'bioclimatic envelope' modeling of wild stocks (recommendation 2B, 2D and 2F) in order to predict localities where conflicts might arise in the future, and where offshore aquaculture should not be permitted.

Theme 5 – Understanding stakeholders & citizens

5A - Stakeholder participation & fisheries governance

In response to statutory requirements concerning the need for an 'ecosystem-based approach to fisheries management' and in line with expectations that climate change will have negative consequences for many fish stocks, it is anticipated that the EU will begin to implement more 'precautionary' regulations than has previously been the case, to ensure that fish stocks are maintained at full reproductive capacity in the future and that ecosystems achieve 'good environmental status' (GES). Whenever stricter regulations are deemed necessary, a top down approach often yields unfortunate consequences in terms of compliance, in particular illegal and unreported fisheries catches, and consequently increased uncertainty in fish stock assessment models in the future. Such concerns can be partially avoided through stakeholder engagement in the decision-making processes, and through better understanding of stakeholder motives. Traditionally fishery scientists have been paid little attention to stakeholder engagement techniques, and as a result relationships have been somewhat fractious and adversarial. Techniques such as mediated modelling (MM) with multi-criteria assessment (MCA) that encourage stakeholder involvement can ensure that impacted individuals (including different fisher groups and environmental NGOs) feel they have a voice, that compliance is enhanced and that opinions and knowledge from the industry are taken into account. There is no single method to involve stakeholders in any given decision, and a number of alternative methods will often need to be employed, sequentially or in combination, to ensure an effective flow of information. A whole body of work exists concerning participatory management techniques, but such approaches have rarely been applied to fisheries and especially so within the context of anticipated future climate change.

Recommendation – Develop participatory management techniques that engage stakeholders in the decision-making process and yet recognize the risks and uncertainties associated with future climate change. Such approaches should aim for consensus regarding necessary future management actions in order to ensure long-term sustainability.

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9 Annex I – Prioritised list of research gaps

See section 7 for explanation and interpretation

Rec No	Knowledge gap	VFM	Im-mediacy	Rele-vance	Wider Benefits	Score	Existing science
4D	Trade-offs between fisheries, conservation and other human activities	4	5	5	4	18	2
3A	Modelling the behaviour of fishers	4	5	5	3	17	1
2E	Fisheries in the Arctic	4	4	5	4	17	1
2B	Understanding & modelling fish behaviour	3	5	5	4	17	3
2H	Ecosystem productivity and carrying capacity	4	5	5	3	17	3
3C	Impacts of climate change on recreational fisheries	4	4	5	3	16	1
1D	Understanding low oxygen events and their consequences	4	3	4	4	15	2
1C	Long-term datasets for climatic monitoring and model validation	5	3	2	5	15	3
2C	Scaling up from OA lab experiments to populations and ecosystems	4	2	5	3	14	2
3B	Adaptive capacity in fishing communities	4	2	4	4	14	2
2G	Biological/ecological data recovery	4	2	4	3	13	4
3D	Adaptability of international fisheries management	4	3	4	2	13	2
3E	Catchability and behaviour of fish in response to fishing gear	2	4	3	4	13	2
1E	Catchment to coast issues	3	2	4	3	12	2
2D	Understanding & predicting changing species interactions	2	2	4	4	12	3
2I	Understanding recruitment uncertainty	3	2	5	2	12	5
4C	Models that consider multiple stress factors	3	2	3	4	12	2
5A	Stakeholder participation and fisheries governance	2	4	3	3	12	3
4F	Aquaculture, fisheries & climate change	3	3	3	3	12	3
1A	Improved Regional Climate Models (RCMs)	3	2	2	4	11	4
2F	The spread of non-native/invasive species	3	3	3	2	11	2
2A	Biological adaptability to climate change	2	1	3	4	10	1
4A	Global economics & trade	2	2	3	3	10	3
4E	Data recovery - socio-economic	3	2	3	2	10	3
1B	Improved Global Circulation Models (GCMs)	1	1	1	5	8	5
4B	Carbon budgets (emissions from fishing vessels, natural sources & sinks)	3	1	1	3	8	2

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