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EXECUTIVE SUMMARY

What is already happening

1. Some fish distributions have moved northwards over the past 30 years by distances ranging from ~50 to 400km with coldwater species such as monkfish *Lophius piscatorius* and snake blenny *Lumpenus lampretaeformis* moving the furthest. At the same time some have moved into deeper waters at an average rate of ~3.6m per decade.
2. There have been many occurrences of rare or unusual fish in UK waters in recent years (including seahorses, ocean sunfish, triggerfish, tuna, stingrays etc.), although this does not necessarily reflect the influence of long-term climate change.
3. Warmer temperatures around the UK are correlated with poor conditions for survival of cod larvae and growth, but enhanced growth rates in sole (a warm-water species).
4. Climate and weather are known to influence year class strength (the number of surviving juveniles) in fish, and warmer conditions in recent years have coincided with poor survival of cod larvae.
5. Diadromous species (which spend some of their life in both fresh and marine waters) such as salmon and eel have been shown to be particularly vulnerable to climate change (water temperature and river flow), with impacts on both freshwater and marine phases.
6. Eel recruitment (the number of returning elvers) has declined throughout the UK. One possibility is that climatic changes in the Sargasso Sea are influencing reproduction and larval survival at sea.
7. Sandeels are an important prey resource for seabirds and marine mammals. Poor 'recruitment' of juveniles in recent years is thought to have been related to warmer temperatures, a positive NAO and a lack of availability of certain key planktonic prey items.

What could happen in the future

1. Attempts have been made to predict the future distribution and productivity of fish stocks around the World, but there are few locally-relevant studies for waters around the UK.
2. Climate change may lead to numerous local extinction and invasion events by the year 2050 with pelagic species (such as herring and anchovy) moving pole-ward by up to 600 km and demersal species (such as cod and haddock) by an average of 223 km.

3. Changes to currents may have an impact on the dispersal of fish eggs and larvae. It is anticipated that winter and early spring spawners (such as cod and plaice) will experience poor larval survival and growth, whereas warm-water, later spawning species (such as sprat) may benefit. Ocean acidification may impact food-webs supporting marine fish but there may also be direct physiological consequences for developing fish larvae that will reduce population sustainability overall.
4. Some diadromous fish species which exist in the UK are predicted to benefit from climate change (warmer temperatures and changed river flows) including Twaité shad and Thin-lipped grey mullet, whereas others such as river lamprey and smelt are anticipated to decline.

FULL REVIEW

Context

More than 330 species of fish are thought to inhabit the shelf seas surrounding the British Isles, and these range in size from the 11m basking shark *Cetorhinus maximus* to gobies and open-water mesopelagic species that rarely reach 1cm in length, even as adults. Fish are found in the deep sea (>1000m depth), in the productive waters around our coasts and some 'diadromous' species migrate from rivers to the sea to spawn (e.g. eels *Anguilla anguilla*) or vice versa (e.g. salmon *Salmo salar*, lampreys, shads). Recent reviews provide strong circumstantial evidence to suggest that ocean climate will have far-reaching effects on the dynamics of fish populations. However, knowledge of the underlying mechanisms and likely future trajectories is rather limited (see Rijnsdorp *et al.*, 2009; Drinkwater *et al.*, 2010). 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 storm events, precipitation patterns, pH and river run off. Second, fish have complex life cycles comprising several life history stages, differing in their sensitivity to climate effects (Graham & Harrod, 2009).

In the following chapter we consider changes that have been observed in the distribution of fish species over the past century, we look at how fish growth rate and larval survival has been influenced by changing climate and we consider the role played by fish in wider marine food-webs (as prey or predators). We then consider what might happen to marine fish in the future, in the face of predicted temperature rises, extreme weather events and ocean acidification. We examine gaps in the current knowledge base and consider some of the socio-economic consequences that might arise as a result of climate impacts on marine fish.

A separate MCCIP review document has been prepared for 'fisheries', and this provides more detail regarding the likely consequences for the fisheries and fish processing sectors.

1. What is already happening?

Changes in fish distribution

Temperature is one of the primary factors (together with food availability, depth, salinity, shelter and suitable spawning grounds) that determine the large-scale distribution patterns of fish. Because most fish species tend to prefer a specific temperature range (Coutant, 1977; Scott, 1982), an expansion or contraction of the distribution range often coincides with long-term changes in temperature. These changes are most evident near the northern or southern-most boundaries of the species' range; theoretically warming results in a distributional shift northward, and

cooling draws species southwards for fish in the northern hemisphere (Rose, 2005). Statistical approaches such as correlation analysis have yielded important information on the historic pattern of change. For instance, the recent warming trend in the north-east Atlantic has coincided with an apparent northward shift in the distribution of fish species from southerly latitudes (Quero *et al.*, 1998; Beare *et al.*, 2004; Perry *et al.*, 2005). A study of 36 species of demersal (bottom-living) fishes using UK fish survey data, indicated that centres of distribution shifted by distances ranging from 48 to 403 km during the period 1977 – 2001 (Perry *et al.*, 2005), however significant shifts were only observed for 15 out of the 36 species examined and it is unclear why 21 species studied in Perry's study (i.e. the majority) showed no apparent change. An important complication in assessing the impact of climate change on fish populations, is to disentangle the effect from that of other drivers such as fishing. Fishing mortality rates have been higher in the southern North Sea than in the north (Heath *et al.*, 2003, Heath *et al.*, 2007), and so apparent changes in distribution (as indicated by Perry *et al.* 2005) could simply be a consequence of local patterns of fishing pressure and different rates of depletion in spatially segregated sub-stocks (Hutchinson *et al.*, 2001; Wright *et al.*, 2006).

Dulvy *et al.* (2008) explored the year-by-year distributional response of the North Sea demersal fish assemblage to climate change over the 25 years from 1980-2004. The centre of gravity of latitude and depth of 28 bottom-dwelling (demersal) fishes was estimated from the autumn English Ground Fish Survey. This study suggested that the whole North Sea demersal fish assemblage deepened by ~3.6 m per decade in response to climate change between 1980 and 2004. The latitudinal response to warming seas was more heterogeneous, and was a composite of at least two patterns: (i) a northward shift in the average latitude of abundant, widespread thermal specialists (grey gurnard *Eutrigla gurnardus* and poor cod *Trisopterus minutus*), and (ii) the southward shift of relatively small, southerly species with limited occupancy and a northern range boundary in the North Sea (scaldfish *Arnoglossus laterna*, solenette *Buglossidium luteum*, bib *Trisopterus luscus*, sole *Solea solea* & lesser-spotted dogfish *Scyliorhinus canicula*). The southward shift of warm-tolerant Lusitanian species is consistent with climate change acting: (i) through the warming and increasing availability of shallow habitats in the southern North Sea and (ii) through North Atlantic Oscillation-linked inflows of warm water into the NE North Sea. In the North Sea the north tends to be colder than south in summer, but the south tends to be colder than the north in winter. Some southern North Sea species were previously excluded from large areas of shallow inshore habitat in winter because these waters cool down to <1 °C. For example, sole tend to over-winter in deeper waters before returning to the shallows in spring, in order to avoid the lethally cold winter temperatures (Henderson & Seaby, 2005). However, there is now anecdotal evidence that sole are arriving inshore earlier due to the rapidly warming seas in winter, in contrast to the severe winters that were experienced in the 1960s, when mass mortality events were reported for Lusitanian species, such as sole and conger eel *Conger conger* (Woodhead, 1964).

In 1996, a paper was published describing long-term variation in the abundance of southern species in the southern North Sea (Corten & van de Kamp 1996) in relation to hydrography. Two periods of increase in the prevalence of southern species were described in the mid-1970s and the 1990s. Both periods coincided with positive temperature anomalies, which in turn correlated with southerly winds over the Netherlands, indicating increased flow of Atlantic water through the Straits of Dover. The authors concluded that the increases were not part of a systematic long-term trend, but the result of increased transport of southern fish species into the North Sea and favourable winter temperatures. Beare *et al.* (2004) revisited this issue in 2004,

and concluded that profound long-term changes are, in fact, occurring. Most species classified as having southern biogeographic affinities exhibited almost exponential increases in abundance since the mid-1990s, (which might be thought to support the case of Corten & van de Kamp, 1996). However, these increases were common to what is a very diverse range of fish species, encompassing a variety of taxa and habitat preferences. The lesser weever *Echiichthys vipera*, for example, is always confined to shallow, southern parts of the North Sea whereas the bluemouth redfish *Helicolenus dactylopterus* is a deepwater shelf-edge species, yet both have shown similar increases since 1990. Poor cod, john dory *Zeus faber*, horse mackerel *Trachurus trachurus*, mackerel *Scomber scombrus*, tub gurnard *Trigla lucerna*, and red gurnard *Aspitriglia cuculus* have all increased in abundance over the past decade, but there were also peaks in the mid- to late 1950s, and mid-1970s, in addition to those observed more recently.

Climate change has been predicted to lead to changes in local and regional species richness through species extinctions and latitudinal ranges shifts. In the North Sea, species richness of fish and fauna increased from 1985 to 2006 which Hiddink & Ter Hofstede (2008) suggested was related to large-scale biogeographical patterns and climate change. Eight times as many fish species displayed increased distribution ranges in the North Sea (mainly small-sized species of southerly origin) compared with those whose range decreased (primarily large and northerly species).

The Thames estuary fish assemblage is composed largely of juvenile individuals that use the estuary as a nursery habitat. Attrill & Power (2002) demonstrated that patterns in the North Atlantic Oscillation (NAO) coincided with variation in the structure of the fish assemblage (explaining 54% of variation). Flatfish and 'northern' species (e.g. herring *Clupea harengus*) showed a negative relationship between abundance and the NAO, whilst those species considered 'southern' (e.g. bass *Dicentrarchus labrax*, sprat *Sprattus sprattus*) showed a positive relationship. The abundance of gadoid fishes, sole and estuarine species such as smelt *Osmerus eperlanus*, pipefish *Syngnathus* spp. and pogge *Agonus cataphractus* was not related to variation in the NAO (Attrill & Power, 2002).

A study of the changing fish community in the Bristol Channel was published in 2007 (Henderson 2007), using data derived from the filter screens of Hinkley Point nuclear power station. This study identified two periods of discrete change in the fish community over the past 25 years. The first change occurred in the late 1980s and involved a shift in the relative abundance of the 'permanent' members of the community. This abrupt event coincided with observed changes in the plankton of the north-east Atlantic (Beaugrand, 2004) and was correlated with the winter NAO. A second discrete change, affecting the total species assemblage, occurred in the early 1990s. This was marked by a sudden alteration in the set of 'occasionally occurring' species. After 1993 these were dominated by species with distributions centred to the south of the Bristol Channel, whereas northerly cold-water species disappeared. This change was correlated with average seawater temperature (and possibly the Atlantic Multidecadal Oscillation - AMO) rather than NAO. In addition to discrete changes in community structure, there has been a continuous increase in fish species richness in the samples collected from the power station.

Analysis of fish taxa in the western English Channel (EC) over a 90 year period indicated that 9 of 33 core species (butterfly blenny *Blennius ocellaris*, dragonet *Callionymus lyra*, topknot *Zeugopterus punctatus*, solenette, poor-cod, lesser-spotted dogfish, greater pipefish *Syngnathus acus*, thickback sole *Microchirus variegatus*, and red bandfish *Cepola rubescens*) responded strongly to increasing sea temperatures (Genner *et al.*, 2004). A parallel analysis of 33 species from power

station intake screens in the Bristol Channel (BC) over 22 years showed similar macroscopic trends, with one species declining in abundance (the sea snail *Liparis liparis*), and 9 increasing (Genner *et al.*, 2004). Somewhat paradoxically, there was a general lack of boreal species increasing during cooling periods (and decreasing during warming periods) compared with responses to climate by southern species. The reason for this asymmetry in responses between species of different biogeographical affinity is not known, but may involve complex indirect processes (Stenseth *et al.*, 2002; Genner *et al.*, 2004).

Many of the species which have expanded in recent years have been non-commercial, planktivorous species such as the boarfish *Capros aper*, which has become particularly prevalent in French and UK survey catches since 1989 (Pinnegar *et al.* 2002). This phenomenon has been reported as occurring elsewhere in the North Atlantic including the Bay of Biscay (Farina *et al.* 1997; Blanchard & Vandermeirsch, 2005) and offshore seamounts (Fock *et al.*, 2002), and in the past *C. aper* outbreaks had been linked to storms and variability in offshore climate (Cooper, 1952). Boarfish are now being landed by Irish fishing boats and converted to fish meal for aquaculture, in excess of 17,608 tonnes were landed in 2007 (Marine Institute, Stock Book 2008).

Climate-driven changes in timing and extent of annual migrations also occur (Sims *et al.*, 2001). Change in migration phenology has been described for the flounder *Platichthys flesus*, which has been shown to undertake a spawning migration 1 – 2 months earlier when conditions are cooler (Sims *et al.*, 2004). This may seem paradoxical at first, given our usual expectation that organisms will migrate earlier during warmer years. In the English Channel region, however, freshwaters, estuaries and shallow marine environments are colder in winter than the deep offshore waters. Flounder make their annual winter migration to these warmer deep waters to breed, and the timing of migration appears to be triggered by the onset of low temperatures. Recently published evidence from ichthyoplankton sampling suggests that other winter breeding species in the English Channel region also spawn earlier in cooler years, while summer spawning fish tend to spawn later (Genner *et al.*, 2010; Greve *et al.*, 2005). Together this evidence suggests that fish spawning and migration phenology may be spatially variable and highly dependent on local differences in thermal regimes.

The effects of climate change on elasmobranch fishes (rays, skates and sharks) are poorly understood, and contrast with what is known about many important teleost fishes. Some elasmobranch fishes are extremely sensitive to temperature variation (*i.e.* as low as 0.001°C: Brown, 2003). Although it is currently unclear how important this sensitivity to temperature might be to their ecology. Many elasmobranchs demonstrate complex behavioural trade-offs that are often associated with temperature (Sims, 2003). Cotton *et al.* (2005) showed that interannual variation in relative abundance of basking sharks off south-west Britain was positively correlated with fluctuations in sea surface temperature (SST) and the NAO. At a local scale (0.01–10 km), basking shark distribution and migration is determined by the abundance of the copepod *Calanus helgolandicus* (Sims, 1999; Sims & Merrett, 1997; Sims & Quayle, 1998), with SST being less important at these small scales (Sims *et al.*, 2003a). However, at greater scales (10–1 000 km) SST correlated significantly with basking shark distribution and movement patterns (Sims & Quayle, 1998; Sims *et al.*, 2000) with more basking sharks observed in warmer waters.

Unusual Occurrences & Outbreaks

Observations of rare or unusual fish in UK waters in recent years (Stebbing *et al.*, 2002), may be related to oceanic warming. Sightings of blue-fin tuna *Thunnus*

thynnus, triggerfish *Balistes capriscus*, thresher *Alopias vulpinus* and blue sharks *Prionace glauca*, sting-rays, and seahorses *Hippocampus* spp. are all becoming more commonplace (Stebbing *et al.*, 2002) as are ocean sunfish *Mola mola* (Houghton *et al.*, 2006) although mechanisms and consequences are poorly understood. Swaby & Potts (1999) made the first British record of the sailfin dory *Zenopsis conchifer*, noting that the species is advancing northwards along the continental shelf west of the British Isles at a rate of 60 km per decade. Similarly, the short-snouted seahorse *Hippocampus hippocampus* seems to be expanding its range northwards, from its stronghold in the English Channel (Pinnegar *et al.*, 2008). Other species which have recently appeared in the North Sea for the first time (or have re-occurred after a very long period of absence) include the violet stingray (*Pteroplatytrygon violacea*), butterflyfish (*Stromateus fiatola*), and broad-billed swordfish, *Xiphias gladius*. However, the occurrence of vagrants and/or unusual species is not necessarily indicative of long-term climate change. Arvedlund (2009) used the example of a hammerhead shark *Sphyrna zygaena* that washed up on the coast near Portreath Harbour, Cornwall in December 2004 (Southall & Sims, 2006), as an example of an observation that should not necessarily be interpreted as reflecting long-term change, since historic records in the 19th Century show that this species had occurred sporadically in the same area in the past. Better systems are now in place to record unusual occurrences (including national databases such as that held by the National Marine Aquarium in Plymouth), and consequently it is difficult to distinguish increased abundance from better information systems. Furthermore, it is likely that rare fish records are self-perpetuating, with the public more likely to report findings if they believe that either a) their catch is newsworthy and/or b) their catch is hard physical evidence of climate change. In recent years, statistical techniques have developed to help detect range shifts on the basis of sporadic and/or historic occurrence records (see Tingley & Beissinger, 2009), such approaches should be used rather than simply assuming that one fish is indicative of a system-wide change.

Changes in fish growth rate

Poikilotherms (cold-blooded animals) such as fish are likely to be greatly affected by temperature change through influences on their metabolic rates and changes in life history processes (Brett, 1979). Brander (2000) found that weight-at-age of North Sea cod *Gadus morhua* in the first year of life was strongly influenced by temperature. Older and larger cod have lower optimal temperatures for growth (Björnsson *et al.*, 2001) and the local distribution of cod is known to depend on depth and temperature (Ottersen *et al.*, 1998; Swain, 2003). Blanchard *et al.* (2005) used information on optimal temperatures for growth and suggested that in years when stock size is low, catches are largely confined to regions with near-optimal bottom temperatures. Conversely, when population size is high, catches are spread across a larger area including regions with sub-optimal temperatures. The authors demonstrated that spatial extent of optimal habitat appears to have decreased from 1977 to 2002, reflecting a gradual warming of the North Sea. This is particularly worrying given that the remaining, highly aggregated, stocks would be especially vulnerable to over-harvesting.

Cod are known to be capable of moving large distances (approx. 1000 km), and hence could theoretically re-locate to anywhere in the North Sea. However, a study by Neat & Righton (2007), based on observations of the temperature experienced by 129 individual cod (using data storage tags), suggested that in the summer most of the individuals in the south experienced temperatures considered sub-optimal for growth. Cooler waters were easily within the reach of these cod and a small number

of individuals migrated to areas that allowed them to experience lower temperatures, indicating that the cod had the capacity to find cooler water. Most however, did not, suggesting that the changing thermal regime of the North Sea might not yet be causing individual cod to seek cooler waters. It is possible that cod could be trading between thermally optimal habitats and requirements for prey, shelter and reproduction.

Pilling *et al.* (2007) examined annulus formation in the otolith (ear bone) of North Sea cod. The authors reported a change in the timing of annulus formation during warm versus cold periods (1985-1986 contrasted against 1994-1995). This study confirmed that southern North Sea cod do experience increased thermal stress during warmer years and that this manifests itself in slower growth rates. The effect of rising seawater temperature on the growth of juvenile sole and plaice *Pleuronectes platessa* was investigated by Teal *et al.* (2008) in the south-eastern North Sea, for the period 1970 to 2004. Increasing winter temperatures significantly increased the growing period of sole, a warm-water species that spawns in spring, but not of plaice, a temperate species that spawns in winter. The higher temperatures observed since 1989 positively affected the quality of the shallow coastal waters as a nursery area for sole but not for plaice. Between 1970 and 2004 mean lengths of 0-group sole increased significantly by over 2 cm. The inter-annual variation was large, and rather than being a steady linear increase, the main increase appeared to have occurred between 1988 and 1990. Length of 0-group plaice varied without a clear trend. In both species the end of the spawning period shifted to an earlier date in recent years, coinciding with increased winter SST. Since the beginning of the 1990s, sole spawning ended ca. 20 days earlier than in the previous 20 yr, but spawning was late again during the cold year of 1996. Although less distinct than for sole, a similar shift to an advanced spawning was observed in plaice ca. 1989, and in 2001 spawning date occurred earlier than at any time in the past 30 yr.

Larval survival and 'recruitment'

Fishermen and scientists have known for over 100 years that the status of fish stocks can be greatly influenced by prevailing weather conditions (Hjort, 1914; Cushing, 1982). Recruitment, 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 group surviving from the annual egg production to be exploited by the fishery. In the case of cod, there is a well established relationship between recruitment and sea temperature (O'Brien *et al.*, 2000; Beaugrand *et al.*, 2003; Clarke *et al.*, 2003). At the northern extremes, warming leads to enhancement of recruitment, whilst around the UK, close to the southern limits of the range, warm conditions lead to weaker than expected year classes, and vice-versa (Drinkwater, 2005).

During the late 1960's and early 1970's, cold conditions were correlated with a sequence of positive recruitment deviations in cod, haddock *Melanogrammus aeglefinus* and whiting *Merlangius merlangus* (Brander & Mohn, 2004), a phenomenon which has come to be known as the 'gadoid outburst' (Heath & Brander, 2001) when stocks increased to hitherto unseen levels. However, in more recent years, a warming climate has prevailed and year class strength has been weaker than average. This in turn has led to a decline in the level of fishing mortality that can be sustained by the stock.

Although there has been 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. Other aspects of the ecosystems inhabited by cod have changed in concert with temperature and these could be

responsible. In particular, the make up of the plankton on which cod larvae feed has changed significantly. The biogeographic boundary between the sub-polar and sub-tropical plankton communities in the north-east Atlantic have moved northwards by approximately 1000 km since 1960, in parallel with the warming of sea surface temperature. The year-class size of marine fish is greatly influenced by the timing of spawning and the resulting match-mismatch with their prey and predators (Cushing, 1990). A clear seasonal shift to earlier appearance of fish larvae has been described for southern North Sea cod and many other species (Greve *et al.*, 2001; 2005), in addition it has been demonstrated that rising temperatures have coincided with marked changes in the zooplankton composition (Beaugrand *et al.*, 2002). There has 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 species has been correlated with recent failures in cod 'recruitment' and an apparent increase in flatfish recruitment (Beaugrand, 2003, 2004; Reid *et al.*, 2001, 2003). *C. helgolandicus* occur at the wrong time of the year and is 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 (Last 1978, 1980), 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. Rowlands *et al.*, (2008) have suggested cod, whiting and haddock larvae in the Irish Sea select a sequence of different prey types as they grow, initially selecting copepod nauplii and small copepods (e.g. *Pseudo/Paracalanus*), however, there is a clear preference for *Calanus* post metamorphosis, even though this species is comparatively rare in the Irish Sea. This sequence of different prey items may make fish recruitment even more susceptible to match-mismatch type effects, i.e. more vulnerable to changes in ocean climate.

Impacts on Diadromous species

A number of species migrate from rivers in the UK to spawn at sea (e.g. eels) or migrate from the sea to spawn in UK rivers (salmon, sea trout *Salmo trutta*, lamprey *Petromyzon marinus*, shads, sturgeon *Acipenser sturio* etc), and 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.

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). Salmon depend on the timing of seasonal events and use environmental variables as migratory cues (Friedland *et al.*, 2003). 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 temperatures (McCormick *et al.*, 1998). Changes in precipitation patterns under future climate change scenarios, may influence the ability of smolts to successfully migrate to sea. Low water flow in rivers can also have a deleterious effect on upstream migration of salmon returning from the sea 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 up to 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 sea-trout, with particular reference to water temperature and river flow. The authors show that climate change will likely impact upon migration, 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. Johnson *et al.* (2009) attempted to outline the possible consequences of climate change in two UK river systems, the Thames and the Yorkshire Ouse. This study suggested that warmer winters and milder springs will favour the recruitment of many coarse fish species, however, warm, slow-flowing, shallower water would make southern UK rivers a less favourable habitat for Atlantic salmon.

Eel recruitment (the number of returning elvers) has declined in most regions where this species occurs throughout the UK, as has the abundance of yellow or silver eels in many river catchments. This reflects an Atlantic-wide down-turn in eel populations that may or may not be related to climate change. The reasons for the decline in eels is not clear – suggestions include changes in oceanic conditions, overexploitation, freshwater habitat destruction, contaminants and introduction of the parasite *Anguillicola crassus* from Asia. Friedland *et al.* (2007) raised concerns that climatic changes in the Sargasso Sea may be influencing oceanic reproduction and larval survival of eels. Ocean-atmospheric changes in the Sargasso Sea may affect the location of spawning areas by silver eels and the survival of leptocephali during the key period when they are transported northeast-wards towards the Gulf Stream. A northward shift in a key isotherm (22.5°C), a declining trend in winds and a shallowing of the mixed layer depth could affect primary productivity in areas where leptocephali feed; but anthropogenic factors during their continental life stage must also be considered.

Fish as food for marine predators

A number of fish species are known to be key prey for natural predators, including seabirds and marine mammals. A lack of availability of these prey resources has been shown to result in poor breeding success and/or starvation of top predators (Frederiksen *et al.*, 2004; MacLeod *et al.*, 2007), and therefore knowledge of how these fish species might be impacted by future climate change is of immediate concern.

There has been much discussion about how long-term climate change might impact sandeel *Ammodytes marinus* populations, and hence have wider implications for fisheries and organisms at higher trophic-levels (e.g. Frederiksen *et al.*, 2004). The recruitment dynamics of sandeels are highly erratic although it had previously been suggested that high abundance of sandeel larvae is directly related to greater penetration of Atlantic water into the North Sea (Hart, 1974). Arnott & Ruxton (2002) conducted an analysis of sandeel population data, both at the North Sea and at the regional scale (years 1983 to 1999). A negative relationship was detected between recruitment and the winter NAO, which affects sea temperatures during the egg and larval phase. Warmer sea temperatures correlated with poorer than average recruitment. This effect was most pronounced in the south-western part of the North Sea, which is near the southern limit of the species' distribution. There was also a positive association between recruitment and *Calanus* abundance around the time of larval hatching, suggesting that the availability of this prey species is important for larval sandeel survival. A recent study by van Deurs *et al.*, (2009) demonstrated that the size of the parental spawning stock (which is affected by the fishery) and the

survival of early larvae (which is affected by climate) are both important determinants on recruitment success in North Sea sandeels and that early egg production in the copepod *C. finmarchicus* is key to successful year classes. Van der Kooij *et al.* (2008) confirmed that sandeel abundance at a local scale was best described by a model that included bottom temperature, water column stratification and surface salinity, however the study showed no relationship between zooplankton density and sandeel distribution (presence/absence) on the Dogger Bank.

Sprat are another key prey resource for natural predators such as marine mammals. The North Sea sprat stock is again, mostly driven by recruiting year classes, and commercial catches in the past have mainly consisted of 1-year old individuals. Data on this species are particularly poor, although the ICES working group responsible for sprat, has acknowledged that the zooplankton community that is sustaining the sprat stock in the North Sea appears to be changing (Beaugrand *et al.*, 2003; Reid *et al.*, 2003). However, sprat is mainly distributed in the southern North Sea where these trends are less dramatic, and thus it is difficult to predict how sprat stocks might respond to future climate change. In the Baltic, MacKenzie & Koester (2004) used 45 years of data and demonstrated that recruitment depends on temperature conditions during the months when sprat gonads, eggs, and larvae are developing. They also demonstrated that recruitment could be predicted before adults spawn, using linkages between recruitment, large-scale climate variability (North Atlantic Oscillation), Baltic Sea ice coverage, and water temperature. The forecasting of sprat year-class strength has recently been revisited by Ojaveer and Kalejis (in press) but it is still the case that little is known about sprat populations in the North Sea and elsewhere around the UK. Peck *et al.* (2009) have used 3-D biophysical modelling to determine how the drift trajectories of sprat eggs and larvae (but also plaice, cod and horse mackerel) might be impacted by future changes in the hydro-climate. This study concluded that we should anticipate reductions in winter and early spring spawners (such as Atlantic cod and plaice) and increases in warmer-water species such as horse mackerel, sprat and other small pelagic fish species as a consequence of changes to ocean currents and retention zones in the region.

A number of warm-water pelagic species have increased in abundance in recent years, most notably sardine *Sardina pilchardus* and anchovy *Engraulis encrasicolus*. Small numbers of anchovy had occasionally and sporadically been caught in the North Sea throughout the 20th Century (Beare *et al.*, 2004), but they seem to have proliferated since 2000, and the species is now widely distributed – over 80% of the area sampled by International bottom trawl surveys (ICES, 2008).

2. What could happen in the future?

Changes in fish distribution

A surprisingly large body of work now exists within which attempts have been made to predict the future impact of climate change on fish stocks and/or fish assemblages. However, much of this work remains highly speculative and modelling approaches that have been applied to terrestrial species for many years have only recently been taken up and turned towards maritime applications.

Modelling strategies for predicting the potential impacts of climate change on the natural distribution of species have often focused on the characterization of a species' 'bioclimate envelope' (Pearson & Dawson, 2003). In other words, by looking at the current range of temperatures tolerated by a species, it is possible to predict future distribution, if we know how the physical environment in an area will likely change in the future. This approach is being applied to fish communities by a number

of research groups across Europe (especially under the EU 'RECLAIM' project). In addition a world-wide analysis has been carried out (Cheung *et al.*, 2009) using this technique, based on 1066 commercial fish and invertebrate species. This study suggested that climate change may lead to numerous local extinction events by the year 2050, especially in sub-polar regions, the tropics and in semi-enclosed seas, with pelagic species (such as herring and anchovy) moving pole-ward by up to 600km and demersal species (such as cod and haddock) by an average of 223km over the next 50 years. Three climate scenarios representing high-, medium- and low- range greenhouse gas emissions were considered, with climate projections generated by the Geophysical Fluid Dynamics Laboratory of the U.S. National Oceanic and Atmospheric Administration (NOAA).

The analysis of Cheung *et al.* (2009) included many species that exist in UK waters (including herring, cod, mackerel, sole, plaice, sprat, whiting and haddock) as well as species that are known to have increased around the British Isles in recent years (including John Dory, red mullet *Mullus surmuletus*, anchovy and seabass). The predicted distribution maps from this study are available at www.seaaroundus.org/ClimateChange/, along with habitat preferences and other parameters used in model construction. A similar bioclimate approach was taken by Bigg *et al.* (2008) to model the distribution of cod in the north Atlantic, although in this case the technique was used to simulate cod distributions in the past, making use of climate model 'hindcasts' for the period around the last glacial maximum (21,000 yr ago).

Scientists from IFREMER (the French marine and fisheries Agency) have used a delta GAM/GLM approach to model future plaice and red mullet distribution in the eastern English Channel and southern North Sea (see Vaz & Loots, 2009). Abundance of each species was related to depth, seabed sediment type, bottom salinity and temperature, bottom shear stress, primary production and zooplankton biomass using outputs obtained from the hydrodynamic and ecosystem model ECOSMO. Results suggest that climate change may strongly impact the future distribution of plaice. For large plaice (>18cm), distribution will still be centred in the southern part of the North Sea, however for young individuals, the predicted distribution is anticipated to shift north-westwards and to the Dogger Bank area in particular. The distribution of small plaice (<18cm) is currently confined to the southern North Sea along the Dutch coast, a region that may become inhospitable in the near future. Red mullet abundance was again divided into young (<17.3cm) and old (>17.3cm) individuals, these were then modelled using a delta GLM approach. A small part of the red mullet population is known to over-winter in the North Sea along the Scottish and English coasts. Model outputs indicate that that the distribution of the red mullet will not change dramatically but that for young individuals, the offshore habitat situated on the Dogger Bank may become more favourable. Older individuals seem little impacted by the change in environment, but they may benefit from higher juvenile survival and expand their area of occupation as a result.

The approach taken by Vaz & Loots (2009) is more simplistic in comparison with that used by Cheung *et al.* (2009), however, it has been applied by researchers at University of Bristol (Steve Simpson, personal communication) in a project aimed at predicting wholesale changes in fish communities around the British Isles (together with researchers from Cefas). At the same time, researchers from IFREMER have used similar methodologies to predict potential spawning habitat of anchovy and sardine in the Bay of Biscay on the basis of hydrodynamic simulations (Planque *et al.*, 2007). GAM models were developed using observational data on anchovy and sardine egg distribution as well as outputs generated by MARS3D, a hydrodynamic

model covering the Bay of Biscay continental shelf. Anchovy spawning habitat appears to be primarily related to bottom temperature but also sea surface temperature and mixed layer depth. By contrast, influence of hydrographic factors on the spawning habitat of sardine seems less clear, but salinity and seasonal stratification seem to be important factors.

There are some concerns about the validity of the bioclimate envelope approach (see Jennings & Brander, 2010). First, it may not be possible to assess temperature preferences from current distributions because the observed distributions are modified by abundance, habitat, predator and prey abundance and competition. Second, there may be barriers to dispersal (although this is typically less of an issue in the sea than on the land) and species will move at different rates and encounter different local ecologies as temperature changes (Davis *et al.*, 1998). A more mechanistic approach has been taken by some authors, whereby the detailed dynamics of individual species are modeled, often by linking complex biophysical models (forced with the outputs from Global Climate Models) to biological sub-routines which replicate the behavior/characteristics of eggs, larvae, juveniles or adults.

One example of this approach is the study of Peck *et al.* (2009), which used outputs from the biophysical circulation model HAMSOM, connected to routines aimed at simulating the drift, distribution and development of fish eggs and larvae in the North Sea. This study quantified drift trajectories, including final position and relative size of the distributional area under different climatic scenarios. Most climate models, including those used by IPCC, assume that the winter NAO index will continue to remain largely positive in the future (although predictions are highly uncertain), in response to increasing concentrations of greenhouse gases. Hence, it is suggested that UK winters will remain “westerly” in nature - milder, windier and wetter. For cod in the North Sea, Peck *et al.* (2009) found that negative NAO years were associated with relatively low sea temperatures and relatively large egg/larvae distribution areas (+400% of the initial spawning area). By contrast, the most positive NAO years (which were also the warmest) were characterized by particle retention in a relatively small ellipse area around the spawning site. Similarly in sprat, years with a high NAO index (>1.5) had the smallest distribution ellipse (~145% initial release area) but these years were not necessarily the warmest. Consequently future climate change will likely inhibit the dispersal of fish eggs and larvae throughout the North Sea, and this could have implications for larval survival if insufficient planktonic food resources are available to support the further development of these animals or aggregations of larvae are more susceptible to intense predation effects (Temming *et al.*, 2007). This modelling work has been taken further in the RECLAIM project (see Daewel *et al.*, 2009) whereby the ecosystem model ECOSMO has been coupled to an NPZD model in order to generate zooplankton ‘prey fields’, and thereby predict the future distribution and survival of cod larvae in the North Sea.

A similar coupled biophysical, individual-based approach has been taken by Huse & Ellingsen (2008) to model the impact global warming on capelin *Mallotus villosus* distribution and dynamics in the Barents Sea, and by Rose *et al.* (2006) to model the impact of future climate change on growth of Pacific herring *Clupea pallasii*.

Reproduction & recruitment

There have been many attempts to include climate variables in single-species population models (e.g. Hollowed *et al.*, 2009), and thereby to predict how the productivity of particular fish stocks will be impacted by climate change in the future. Particular emphasis has been placed on climatic determinants of fish recruitment,

and indeed several studies have inserted temperature or other environmental terms in the 'stock-recruit' relationship in order to make projections into the future.

Clarke *et al.* (2003) used projections of future North Sea surface temperatures and estimated the likely impact of climate change on the reproductive capacity of the cod stock, assuming that the high level of mortality inflicted by the fishing industry (in 2003) continued into the future. Output from the model suggested that the cod population would decline, even without a significant temperature increase. However, scenarios with higher rates of temperature increase resulted in faster rates of decline. In a re-analysis by Kell *et al.* (2005), the authors modelled the effect of introducing a 'cod recovery plan' (as being implemented by the European Commission), under which catches were set each year so that stock biomass increased by 30% annually until the cod stock had recovered to around 150,000 tonnes. The length of time taken for the cod stock to recover was not greatly affected by the choice of climate scenario (generally around 5-6 years), however, overall productivity was impacted and stock biomass (SSB) once 'recovered' was predicted to be considerably less than would have been the case assuming no temperature increase (251,035 tonnes compared to 286,689 tonnes in 2015). The overall message from this study was that in the short term, climate change has little effect on stock recovery, which depends instead upon reducing fishing effort to allow existing year classes to survive to maturity. In the longer term however, climate change may have a greater effect on stock status, and that the North Sea cod stock will only be able to support a sustainable fishery in the future at much lower levels of fishing mortality (i.e. the 'maximum sustainable yield' will be reduced).

Drinkwater (2005) reviewed the possible impact of future climate change on cod and 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 future 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. In addition, spawning sites will be established further north than currently is the case, and it is likely that spring migrations will occur earlier and autumn returns will be later.

Ocean acidification & fin-fish

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. Gazeau *et al.*, 2007; Cooley & Doney 2009). 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. Even though commercial fin-fishes may be less impacted (in comparison with many shellfish) in terms of direct physiological effects, they may be impacted by 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).

Based on laboratory experiments involving cod (at the Ardtoe fish hatchery in Argyll) Le Quesne & Treasurer (submitted) demonstrated that ocean acidification might also inhibit larval development and egg fertilisation success. This, in turn, could greatly

affect recruitment to fish stocks, with important consequences for long-term sustainability. A recent study on coral reef fish (Munday *et al.*, 2009) has shown that larval fish reared in control seawater (pH 8.15) discriminated between a range of cues that could help them locate reef habitat and suitable settlement sites. This discriminatory ability was disrupted when larvae were reared in conditions simulating CO₂-induced ocean acidification. Larvae became strongly attracted to olfactory stimuli they normally avoided when reared at levels of ocean pH that could occur ca. 2100 (pH 7.8) and they no longer responded to any olfactory cues when reared at pH levels (pH 7.6) that might be attained later next century on a business-as-usual carbon dioxide emissions trajectory. If acidification continues unabated, the impairment of sensory ability may reduce population sustainability of many marine species, with potentially profound consequences for marine diversity. Checkley *et al.* (2009) exposed larval white seabass (*Atractoscion nobilis*) to elevated CO₂ (lower pH) waters and found that otoliths (ear bones) grew larger than was the case in unacidified waters. It is unclear whether larger otoliths would have a deleterious effect on the fish; otoliths are used primarily for orientation and to gauge acceleration. Other authors (H. Kurihama, P. Munday, A Ishimatsu pers. comm. 2010) have examined development in fish exposed to acidified waters and have observed no impact on otolith size or structure. Munday *et al.* (2009) exposed spiny damselfish *Acanthochromis polyacanthus* to high CO₂ water and found no change in skeletal development overall (including otoliths) and also no change in swimming performance, growth or metabolism. By contrast, Ishimatsu *et al.* found that high CO₂ and warm temperature together resulted in high larval mortality in the clownfish *Amphiprion ocellaris* and in the meduka (*Oryzias javanicus*). Also, at very high CO₂ concentrations, growth and gonad development were impacted in *Sillago* (an important food fish in east Asia).

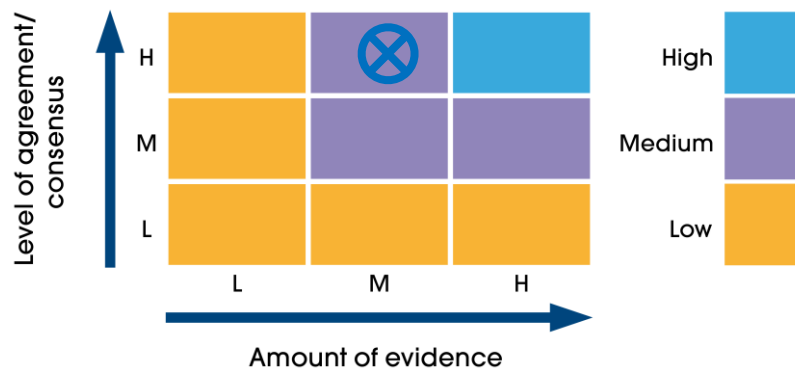
Predictions for diadromous species

Lassalle & Rochard (2009) investigated the potential distribution of diadromous fish found in Europe, North America and the Middle East using a bioclimate envelope approach together with outputs from the HadCM3 (Hadley Centre Coupled Model version 3) global climate model. The authors obtained maps of climatically suitable and unsuitable basins, as well as percentages of contraction or expansion of each species (a similar approach to that used by Cheung *et al.*, 2009). Each model used temperature and/or precipitation as explanatory variables. Responses to climate change were species-specific but could be classified into three categories: little or no change in the distribution (five species), expansion of the distribution range (three species gaining suitable basins mainly northward) and contraction of distribution (14 species losing suitable basins). With regard to species that exist in the UK the Twaite shad *Alosa fallax* was predicted to increase in abundance in Scotland and Ireland, as was the Thin-lipped grey mullet *Liza ramada*. Salmon and marine lamprey *Petromyzon marinus* populations were predicted to remain high and intact in the UK, whereas the river lamprey *Lampetra fluviatilis* were predicted to diminish in the south of the British Isles. Smelt was predicted to lose a huge part of its distribution area, but Irish and Scottish basins were expected to remain favourable.

Davidson & Hazlewood (2005) in a report for the UK Environment Agency, predicted that freshwater growth of *S. salar* will increase in the south-west and north of England and Wales under the UKCIP02 low emissions scenario but could fall below current growth rates under the high emissions scenario. They warn that growth rates from salmon in rivers in the south-east of England are likely to decline and that this could have adverse consequences for survival and abundance in this region.

3. Confidence in the science

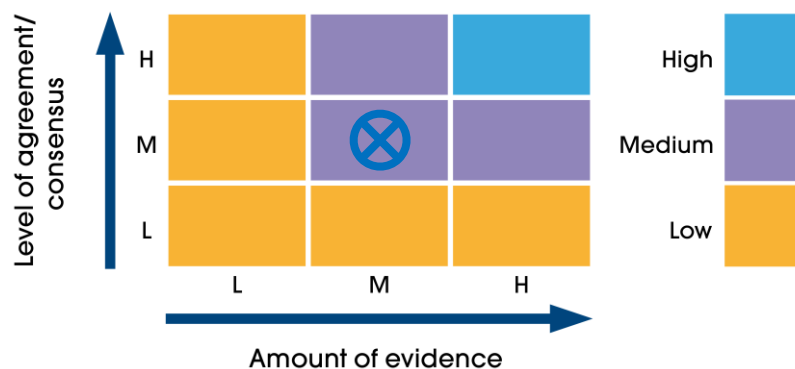
What is already happening: **Medium**



In general there is probably more information available about fish than any other component of marine ecosystems, and there have even been specific reviews of likely consequences of climate change for fish species in the British Isles (e.g. Graham & Harrod, 2009).

For cod in particular, there are extensive data and there have been many published analyses. Consequently we can say with high confidence that climate change has compromised the ability of the stock to withstand fishing mortality, but also that fishing mortality has impacted the ability of the stock to withstand variable climate. Fishing mortality rates that were considered sustainable 30 years ago, are now unsustainable due to negative effects of climate on recruitment. However, at present we are 'not sure' of the precise mechanisms by which climate change affects recruitment, beyond that the effects are correlated with sea temperature and to some extent with plankton abundance and composition. For other commercially important species (e.g. plaice, herring, mackerel, haddock, sole etc.) we have only medium or low confidence in the effects of climate change. Even less is known about the likely responses of non-commercial species, largely because of a lack of data spanning a sufficiently long time interval to analyse changes. Some species of non-commercial species are known to have increased in recent years (e.g. the boarfish and solenette) but it is unclear how this may relate to climate, or whether such changes have been caused by intensive fishing (van Hal *et al.*, 2009). Nevertheless, we can say with high confidence that since 1980 the distribution of many warm-water northeast Atlantic fish species has shifted northwards to occupy latitudes at which they were previously unobserved or rare.

What could happen: **Medium**



Studies have now been carried out that attempt to predict the likely future distribution or productivity of fish species worldwide, however these have very rarely been 'down-scaled' to the level of the United Kingdom or British Isles. Consequently our knowledge of, and confidence in, future projections remains moderate, although slightly higher than was the case in 2007-2008. More research is needed into the likely consequences of ocean acidification for marine fish, but also predictive studies that can distinguish between the possible influences of drivers such as intensive fishing, habitat degradation as well as climate change.

4. Knowledge gaps

Research areas where data or knowledge are insufficient:

- 'Real' information about the linkages between larval fish (their survival and feeding), zooplankton and climate.
- Information for the west of the British Isles. The North Sea has been considered in much greater detail in comparison with western Scotland, the Irish and Celtic Seas.
- Predictive studies (relevant to the UK), attempting to estimate changes in fish distributions, interactions between fish species as a result of changing distributions, the ecological role of incoming species, and prospects for stock recovery and rebuilding.
- We know that abundance and distributional changes have not been consistent in all species, but we do not understand why.
- A key question is how fisheries and climate interact, including whether fisheries remove the ability to buffer against climate change, and whether fisheries (by removal of the largest, oldest and potentially most fecund individuals) prevent species from rapidly benefitting during years with favourable thermal regimes.
- We still know relatively little about how climate has affected the macroecological properties of the UK marine fish assemblage. It would be useful to know if our seas will become more or less productive, whether mean individual body size of the fish assemblage will change, and whether this will impact on other species (including humans).
- There is a significant knowledge gap about climatic influences on the abundance, temporal and spatial distribution of key forage fish species of importance to seabirds and marine mammals. In the UK we do not collect the spatially and temporally-explicit data required to investigate how forage fish abundance affects the distributions, migrations and breeding success of these high profile marine organisms.
- The potential implications of ocean acidification for fin-fish; both indirect consequences through the marine food web, but also direct physiological effects.
- Predictive and experimental studies aimed at elucidating the possible consequences of climate change for diadromous species, and most notably eels and salmon in the UK. It remains very unclear whether climatic influences during the marine phase are having negative consequences for 'recruitment' of elvers or retuning adults to some UK catchments.

- The impact of climate change on non-commercial species, but also fishes in the deep sea and open ocean.
- The ability of fish to 'adapt' (both physiologically and behaviorally) to long-term climate change.
- The potential impact that incoming non-native species or marine pathogens might have on 'native' fish populations, if they were to become established as a result of warmer waters or changing transmission routes (e.g. via an ice-free Arctic).

5. Socio-economic impacts

A detailed review of possible consequences of climate change for commercial fisheries (fin-fish and shellfish) is provided in a separate MCCIP report. The main conclusions of this report are:

- The location where high catches of cod, haddock, plaice and sole occur, as reported by UK commercial fishing vessels, seems to have shifted over the past 80-90 years. However, it remains unclear whether this has been due to long-term climate change or other factors.
- Climate change may be having an impact on the effectiveness of marine protected areas and on the apportionment of fishery resources between neighbouring countries.
- New fisheries have developed for a number of warmer-water species including seabass, red mullet, anchovy and squid. The biomass of seabass in the Channel has quadrupled since 1985.
- Ocean acidification may pose a significant threat to the UK shellfish industry, but the implications are poorly understood.
- The UK as a whole is expected to benefit from slightly enhanced fishery yields (by ~1-2%) over the next 50 years, although there will be regions where overall fishery yields may be reduced (e.g. the Irish Sea and Channel).
- Simulations suggest that cod stocks in the Celtic and Irish Seas are expected to disappear altogether by 2100, while those in the North Sea will decline. Climate change has been 'eroding' the maximum sustainable yield of cod in the North Sea by ~32,000t per decade.
- Very little work has been carried out on the social and economic implications of climate change for the UK fishing industry, however calculations suggest that consequences will be significant only for fishery-dependent communities in the North of Scotland and in the SW of England.

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