MCCIP Marine Climate Change Impacts Partnership

Topic
Fish and Fisheries

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Executive summary
Fish   - Abundances of warm-water fish species (e.g. red mullet, john dory, triggerfish) have increased in UK waters during recent decades, while many coldwater species have experienced declines.   - There has been a massive influx of snake pipefish to UK waters since 2004, but unusual fish occurrences or sudden proliferations of species cannot definitively be attributed to climate change.   - A number of commercial and non-commercial fish species are suggested to have exhibited shifts in mean latitude over the past 25 years.   - Poor 'recruitment' in traditional fishery target species such as cod, plaice and herring may be related to a shift in the composition of **zooplankton**, which are a key prey for developing larvae.   - In some parts of the southern North Sea, cold-water species, such as cod and eelpout, have been shown to experience metabolic stress during warm years, as evidenced by slower growth rates and difficulties in supplying oxygen to body tissues.   - Climate change will have far-reaching impacts on the dynamics of fish populations, however knowledge of underlying mechanisms is rather limited, especially in non-commercial species.

Fisheries

- Excessive fishing pressure has caused fish populations to become more vulnerable to short-term natural climate variability by removing the oldest individuals, and making such populations less able to 'buffer' against occasional poor year classes.
- In the short term, climate change will have little influence on fish stock recovery, which depends instead upon reducing fishing effort to allow existing year classes to survive to maturity.
- Climate-related shifts in species distribution, behavior and depth preference may affect the 'catchability' of certain stocks to fishing fleets.
- Long-term climate change may affect the overall productivity of fish stocks in a given area. Some species may be adversely affected leading to reductions in sustainable yield whilst others, for example seabass, red mullet and John Dory, may be positively affected leading to enhanced fishing opportunities.

Full review

What we currently know about fish & climate

Recent reviews for the North Atlantic provide strong circumstantial evidence to suggest that ocean climate may have far-reaching effects on the dynamics of fish populations and fisheries. 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 storm surges, 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. In addition, fish populations comprise only part of an intricate network of ecosystem components and hence may be influenced indirectly through changes in predation and competitive processes, as well as the changing incidence of disease or harmful algal blooms both of which are expected to increase as waters warm.

Fish are thermal conformers and in most species body temperature is effectively that of the surrounding water, *i.e.* they are ectotherms (FSBI, 2007). Temperature has long been recognised as a major influence on the ecology and the physiology of fish. Enzymatic rates are strongly temperature-dependent; hence temperature is a key determinant of an individual's physiological and biochemical (vital) rates (Clarke, 1993; Coutant, 1987; Fry, 1971; Regier *et al.*, 1990), and influences behaviour (Kramer *et al.*, 1997; Sims *et al.*, 2006). Temperature variation influences almost all aspects of a fish's ecology: *e.g.* hatching and development time of eggs and larvae (Fonds, 1979; Pauly & Pullin, 1988; Rombough, 1997), activity (Koch & Wieser, 1983), oxygen demand (Clarke & Johnston, 1999), swimming performance (DiMichele & Powers, 1982), distribution (Coutant, 1987; Kramer *et al.*, 1997; Sundby, 2000), growth (Brander, 1995), maturation (Svedäng *et al.*, 1996),

immune function (Le Morvan *et al.*, 1998), the phenology of migration (Sims *et al.*, 2004), foraging rate (Elliott & Leggett, 1996; van Dijk *et al.*, 2002), production (Schlesinger & Regier, 1982), reproductive success (Planque & Frédou, 1999), availability of prey (Heath, 2005a,b), predation risk (Elliott & Leggett, 1996) and mortality (Brett, 1979; Fry 1971; Griffiths & Harrod, 2007; Pauly, 1980; Petersen & Kitchell, 2001). Understandably, temperature is considered as a fundamental component of the niche of fishes (Magnuson *et al.*, 1979; Magnuson & Destasio, 1997; Tracey & Christian, 1986).

Abundance & productivity

In several ocean basins, fluctuations in fish populations are known to correlate with decadal scale variability in ocean climate. **Pelagic**🗗 fisheries resources off the west coast of South America are known to change periodically in relation to the El Niño Southern Oscillation (ENSO). In the North Atlantic, many studies have reported decadal scale changes in ecosystems and variability in fish populations that coincide with changes in the NAO index (the air pressure difference between Iceland and the Azores).

Long-term observations reveal that fish species can exhibit temporal 'sign-switching' (Parmesan & Yohe, 2003), where relative abundances of temperate species increase during periods of warming, and decrease when temperatures cool, whereas boreal species show the opposite trend (Southward *et al.,* 1995). Abrupt changes in fish abundance and spawning behaviour have also occurred in response to apparent climate regime shifts (McFarlane *et al.,* 2000; Reid *et al.,* 2001).

Fish scales recovered from **varved sediments**🗗 in various regions of the world (Baumgartner *et al.* 1992; O'Connell and Tunnicliffe, 2001) reveal large fluctuations in species abundances extending back over millennia, which can only be a consequence of climate fluctuations. Sardine populations in the Santa Barbara basin are known to have undergone at least nine major collapses and subsequent recoveries over the past 1700 years (Baumgartner *et al.* 1992). Fish scales in sediments off the upwelling zone off central Peru (Devries & Pearcy, 1982) and in an upwelling region along the coast of South Africa/Namibia (Struck *et al.* 2002; Shackleton, 1987) reveal dramatic fluctuations over the past 3200 years as well as fundamental changes in oceanographic and ecological conditions in the **Humboldt**🗗 and **Benguela**🗗 Current ecosystems.

Alheit & Hagen (1997) compiled data on weather conditions and commercial landings of herring and sardine at fishing ports in Brittany, Normandy, southwest England, Sweden and Norway extending back to the late-10th century. The fisheries were episodic and highly correlated with the mildness/severity of winter weather conditions. Sequences of years with large landings of herring from Swedish coastal waters, off southwest England, eastern English Channel and Bay of Biscay were characterised by cold, severe winter weather conditions in northwest Europe. In particular, herring fisheries flourished towards the southern edge of the latitudinal range during

sequences of cold years in the 'Little Ice Age' (1300-1850). These periods alternated with sequences of years of mild winter weather in which the Swedish, English and French herring fisheries failed, but large landings of herring recorded from more northerly Norwegian coastal waters, and of sardines from southwest England and the English Channel. Such conditions occurred between the mid-12th century and the end of the 13th century (the 'Medieval Warm Period') and during the late 19th to early 20th centuries. The alternation of sardine and herring off southwest England has been noted since the 16th century and has been clearly related to sea temperature and alternations between warm and cold-water plankton species (referred to as the 'Russell Cycle'; Southward *et al.*, 1988). However, when the Cycle changed from a warm-water to a cold-water regime between 1965 and 1979, herring failed to return to the south coast of England, possibly because intensive fishing during the 1920's caused collapse of the stock.

Variability in European sardine (*Sardina pilchardus)* stocks are known to be strongly linked to climatic cycles. Moura & dos Santos (1984) demonstrated a strong lagged correlation between solar activity, as evidenced by sunspots, and production of sardine off the Portuguese coast between 1901 and 1981. Spectral analysis revealed 10.4-year cycles for both sunspots and sardine catches, with high catches of sardines following 1-2 years after a low in solar activity.

Using a 24-year time series of recruit surveys, Henderson & Seaby (2005) confirmed a strong positive correlation between spring temperature and sole abundance in the Bristol Channel. Furthermore, juvenile size was strongly and positively correlated with the NAO, a result supported by work in the Thames Estuary (Attrill & Power, 2002). These observations prompted Henderson & Seaby (2005) to conclude that increased primary and secondary production, associated with the increasingly positive trend in the NAO led to enhanced growth and abundance of sole through increased food availability and higher temperatures in the Bristol Channel and that this trend probably extended over the entire south-western region of Britain.

Changes in distribution

Temperature is one of the primary factors, together with food availability and suitable spawning grounds, in determining the large-scale distribution patterns of fish. Because most fish species or stocks 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 boundaries of the species range; theoretically warming results in a distributional shift northward, and cooling draws species southwards for both warm- and cold-water species (Rose, 2005). Statistical approaches such as correlation analysis have yielded important information on the pattern of change. For instance, the recent warming trend in the northeast Atlantic has coincided with an apparent northward shift in the distribution of fish species from southerly waters (Quero *et al.* 1998; Perry *et al.* 2005, Beare *et al.* 2004). Seabass and red mullet populations around British coasts have been growing

in recent years. Similarly sightings of blue-fin tuna, triggerfish, thresher and blue sharks, sting-rays, turtles and seahorses are all becoming more commonplace (Stebbing *et al.* 2002). A recent study by Perry *et al.* (2005) suggested that distributions of both exploited and non-exploited North Sea fishes have responded markedly to increases in temperature, with nearly two-thirds of species shifting in mean latitude over 25 years. These authors suggest that further temperature rises are likely to have a profound impact on commercial fisheries through continued shifts in distribution and alterations in community interactions.

The mean latitude of species such as Atlantic cod (*Gadus morhua*) and anglerfish (*Lophius piscatorias*) shifted north in relation to warming whereas mean latitude did not change for some species; rather a shift to deeper, cooler depths was evident (e.g. plaice *Pleuronectes platessa*, cuckoo ray *Leucoraja naevus*) (Perry *et al.,* 2005). Hedger *et al*. (2004) also analysed the survey distributions of cod and haddock in the North Sea. These authors showed that cod were found in deeper water during 1990-1999 compared to 1980-1989, but their distribution with respect to temperature was unchanged.

Brander *et al. (*2003) suggested that sardines and anchovies have moved northward and have extended their ranges to include western Norway in recent years. Anchovy and sardine were almost totally absent from the North Sea until the mid 1990s, however small numbers had occasionally and sporadically been caught in ICES area 4a (the North) since 1925 (Beare *et al.* 2004). In 1996, a paper was published describing the 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 (mid-1970s and 1990) using data from the International Bottom Trawl Surveys (IBTS). 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.* 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 though 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, for example, is always confined to shallow, southern parts of the North Sea whereas the bluemouth is a deepwater shelf-edge species, yet both have shown similar increases since 1990. Poor cod, john dory, horse mackerel, mackerel, tub gurnard, and red gurnard 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.

The invasion of the northern North Sea by bluemouth has been noted previously by Dutch scientists (Heessen et al. 1996). The main 'invasion' took place in 1991, after which the abundance increased steadily up until the late 1990s. Abundance then began to diminish, and no bluemouth were recorded in Quarter 1 of 2004. Examination of the length-frequency data for bluemouth suggests that there have been two main recruitments. The first occurred in 1991 and the second in 1998. Heessen et al. (1996) suggested that the large pulse of oceanic water that entered the North Sea in 1990 (Heath et al. 1991) might have transported bluemouth eggs and larvae into the area, which then developed gradually within the North Sea. The study of Beare et al. (2004) adds further weight to that theory since the influx of small bluemouth individuals noted in 1998 were probably related to eggs and larvae transported by another large Atlantic input that occurred during November and December 1997 (Edwards et al. 1999).

Abundances of some warm-temperate and temperate fish species with southern distributions have increased in southern UK waters during recent warming periods (1950s, 1980s-2002), while declines were apparent during cooling episodes (1920s, 1960-70s). Analysis of fish taxa in the western English Channel (EC) over a 90 year period indicated that 9 of 33 core species (butterfly blenny, dragonet, topknot, solenette, poor-cod, lesser-spotted dogfish, greater pipefish, thinkback sole, and red bandfish) responded strongly to increasing sea temperatures (Genner *et al.,* 2004). A parallel analysis of 33 species from power station screens in the Bristol Channel (BC) over 22 years showed similar macroscopic trends, with one species declining in abundance with warming (the sea snail *Liparis liparis*), and nine 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 reasons 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). Swaby & Potts (1999) made the first British record of the sailfin dory *Zenopsis conchifer* in 1999, noting that the species is advancing northwards along the continental shelf west of the British Isles at a rate of 60 km per decade.

Despite identification of clear trends within a region, there appears to be a lack of similarity in responses between sub-regions. Effects of climate vary markedly between adjacent geographical areas, suggesting that broad-scale predictions of future responses will be difficult (Genner *et al.,* 2004). For example, comparison of the aforementioned studies in the English Channel and Bristol Channel demonstrate that nine species in each region responded strongly to increasing sea temperature. However, the same species did not show congruent trends between sites. This highlights the need to understand the mechanisms underlying observed trends, which at present remain little known (Stenseth *et al.,* 2002).

The Thames estuary fish assemblage is composed largely of juvenile individuals that use the estuary as a nursery habitat (FSBI 2007). Attrill & Power (2002) demonstrated that patterns in the NAO coincided with variation

in the structure of the fish assemblage (explaining 54% of variation), the growth of many juvenile residents (76% of variation) and the abundance of many of the dominant species (69% of variation). Flatfish and 'northern' species (*e.g.* herring) showed a negative relationship between abundance and the NAO, whilst those species considered 'southern' (*e.g.* bass, sprat) showed a positive relationship. The abundance of gadoid fishes, sole and estuarine species such as smelt, pipefish and pogge was not related to variation in the NAO (Attrill & Power, 2002).

Heath (2007) looked at patterns in international fisheries landings data for the whole northeast Atlantic region, covering 341 taxonomic categories broadly assigned to five dietary guilds. Densities of landings of each species category (tonnes per km^2) were summed over all nations for decadal periods (1973-1979, 1980-1989 and 1990-1999), and expressed as a proportion of the total northeast Atlantic landings. Changes in the density-weighted mean latitude of landings of each species indicated both northerly and southerly shifts between decades. More species shifted south than north between the 1970s and 1980s, and vice versa between the 1980s and 1990's. On face value this seems to parallel the interdecadal changes in sea and air temperatures, both of which show a cooling between the 1970s and 1980s, and warming between the 1980s and 1990s.

Among the pelagic species, the distribution of landings of herring, mackerel and horse mackerel underwent northerly shifts during both inter-decadal periods. The northerly extension of horse mackerel landings reflects the well documented establishment of a fishery for this species in the North Sea during the late 1980s where commercial quantities had not previously been found (Reid *et al*., 2001). Similarly, the northerly shift in Atlantic mackerel landings reflects a well documented northerly shift in spawning grounds and a change in the migration timing of adults (Walsh *et al.*, 1995).

Disentangling the effects of fisheries and climate

An important complication in assessing the impact of climate change on fish populations is to disentangle its effect from the effect 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 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). Daan *et al.* (2005) also raised the issue of more rapidly declining populations in the south of the North Sea compared to those in the North, whilst highlighting an absolute and relative increase in abundance of the smaller size classes and species. The effect of fishing may thus interact with the effect of climate and have enhanced the apparent northward shift of the smaller sized fish species reported by Perry *et al.* (2005) and more recently by Rindorf & Lewey (2006).

In the Celtic Sea, Blanchard *et al.* (2005b) suggested that smaller, pelagic species have become more abundant in relative and absolute terms,

presumably driven by changes in climate, whereas large commercial species such as cod have largely disappeared due to fishing. 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 (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 have been linked to storms and variability in offshore climate (Cooper 1952).

Migration

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). Timing of flounder migration is driven to a large extent by short-term, climate-induced changes in thermal resources linked to negative (cool) phases of the NAO. Hence short-term climate fluctuations have significant effects on the timing of fish peak abundance in an area, which may have implications for fisheries (Sims *et al.,* 2004).

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 (*e.g.* 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 **elasmobranches** demonstrate complex behavioural trade-offs that are often associated with temperature (Sims, 2003). Cotton *et al.* (2005) showed that a major component of the interannual variation in relative abundance of basking sharks off southwest Britain was positively correlated with fluctuations in sea surface temperature (SST) and the NAO. Their results indicate that climatic forcing of the copepod *C. helgolandicus*, influenced basking shark abundance. At a local scale (0.01–10 km), basking shark distribution and migration is determined by the abundance of adult *C. 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 (10–1000 km) SST correlated significantly with basking shark distribution and movement patterns (Sims & Quayle, 1998; Sims *et al.*, 2000). These observations indicate that although prey density is a key factor in determining short-term distribution patterns, long-term behavioural choices by these **ectothermic** planktivores may relate more closely to occupation of an optimal thermal habitat that acts to reduce metabolic costs and enhance net energy gain (Crawshaw & O'Connor, 1997; Sims *et al.*, 2003b).

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). 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, 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).

Recruitment

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, 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. In the case of cod, there is a well established relationship between recruitment and sea temperature (Beaugrand *et al*., 2003; O'Brien *et al*., 2000; Clarke *et al*., 2003). At the northern extremes, warming leads to enhancement of recruitment, whilst in the North Sea, close to the southern limits of the range, warm conditions lead to weaker than expected year classes, and vice-versa.

During the late 1960s and early 1970s, cold conditions were correlated with a sequence of positive recruitment deviations in cod, haddock and whiting (Brander & Mohn, 2004), a phenomenon which has come to be known as the 'gadoid outburst' (Heath and Brander, 2001) when stocks increased to hither to 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. Contrary to scientific advice, fishing mortality rates in North Sea cod increased steadily from the 1970s to the early 2000s throughout the period of warming, and the net result has been a progressive decline in the stock abundance. Calculations show that the North Sea cod stock could still support a sustainable fishery under a warmer climate but only at very much lower levels of fishing mortality (Cook & Heath, 2005).

In 2006 the ICES Working Group on the Assessment of Northern Shelf **Demersal** Stocks (WGNSDS) considered the influence of sea temperatures on cod recruitment in the Irish Sea (ICES 2006). The time series of Irish Sea cod recruitment exhibited a decline in the 1990s, coincident with an increase in SST. Analysis revealed a clear tendency for strong recruitment residuals to

coincide with prominent negative SST residuals, and for weak recruitment to coincide with strong positive SST residuals. Further biological studies are needed to establish the causal mechanisms for any association between cod recruitment residuals and temperature, before such an association could be considered to have any predictive power for fish stocks in the future.

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. Other aspects of the ecosystems inhabited by cod have changed in concert with temperature and these could be responsible. In particular, the composition of the plankton on which cod larvae feed has changed. The biogeographic boundary between the sub-polar and sub-tropical plankton communities in the northeast Atlantic have moved northwards by approximately 1000 km since 1960, in parallel with the warming of SST. 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). This was confirmed recently on the basis of satellite remote sensing data and a long-term data set of haddock recruitment (Platt *et al.* 2003). A clear seasonal shift to earlier appearance of fish larvae has been described for the southern North Sea (Greve *et al.*, 2001), 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 are the wrong size to be of use to emerging cod-larvae. However because *Calanus* (of either species) is not a major prey item for fish larvae in the southern North Sea (Last 1978a,b, 1980), several authors have argued that this match-mismatch hypothesis does not provide a full explanation for recent failures in fish recruitment throughout the wider region.

Climate-induced changes in species interactions will make prediction of future changes in fish populations problematic (Beaugrand *et al.,* 2003), especially since the climate-envelope approach to predicting species' responses to climate change does not take into account of such complexities, that can yield counter-intuitive species abundance changes (Davis *et al.,* 1998; Southward *et al.,* 2004).

Herring are highly mobile, rely on short, plankton-based food chains, are highly fecund and show plasticity in growth, survival and other life-history traits. These biological characteristics make them sensitive to environmental forcing and highly variable in their abundance (Alheit & Hagen, 1997). Nash & Dickey-Collas (2005) reported a positive relationship between abundance of herring early larvae and winter bottom temperature in the North Sea. They

concluded that the relationship probably reflected a direct physiological effect of temperature on growth and development rates. However, higher abundance of juvenile herring was associated with colder temperatures, possibly reflecting higher *Calanus* abundance, which was itself inversely correlated with winter bottom temperatures (Nash & Dickey-Collas, 2005). Axenrot & Hansson (2003) attempted to relate Baltic herring recruitment with the density of young-of-the-year (YOY) fish (estimated from acoustic survey data), spawning stock biomass and climate (NAO). All factors were positively (if weakly) correlated with year class strength (YCS), but when combined, there was a strong positive relationship with YCS (adjusted R^2 = 0.93), and the authors stressed the significance of climate change to recruitment in this stock.

Sandeels (*Ammodytes* spp.) are a key prey item for many predatory species in the northeast Atlantic, including seabirds, marine mammals (seals and cetaceans) and commercial fish stocks such as cod and whiting (MacLeod *et al.* 2007). A commercial fishery for sandeels began in the 1950s and expanded to become the largest single-species fishery within the North Sea, with recent landings ranging from 0.6 to 1 million tonnes. Consequently, there has been much discussion about how long-term climate change might impact sandeel 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. One reason for this is that the species is short lived. Most individuals are sexually mature at 2 yr (Macer 1966, Gauld & Hutcheon 1990), and few survive beyond 3 to 4 yr because of their high natural mortality rate. Thus, spawning-stock biomass is highly dependent upon recruitment in recent years. Arnott & Ruxton (2002) conducted an analysis of sandeel population data 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 period. Warmer sea temperatures correlated with poorer than average recruitment. This effect was most pronounced in the southwestern part of the North Sea, which is near the southern limit of the species' distribution. There was a positive association between recruitment and *Calanus* copepod (Stages V and VI) abundance around the time of larval hatching, suggesting that the availability of this prey species is important for larval sandeel survival. The authors suggested that future climate change may significantly impact upon sandeel populations in the North Sea.

Sprat (*Sprattus sprattus*) are another key prey resource for many 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 recently acknowledged that the zooplankton community that is sustaining the sprat stock in the North Sea appears to be changing (Reid *et al.*, 2003; Beaugrand *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) recently examined the processes controlling

sprat recruitment and noted that recruitment varies widely between years and is virtually independent of the biomass of mature animals. Using 45 years of data the authors demonstrated that recruitment depends on temperature conditions during the months when sprat gonads, eggs, and larvae are developing. They also show that recruitment can be predicted before adults spawn, using linkages between recruitment, large-scale climate variability (NAO), Baltic Sea ice coverage, and water temperature.

Growth & metabolism

Poikilotherms such as cod 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 in the first year of life was strongly influenced by temperature, a hypothesis confirmed by Björnsson & Steinarsson (2002) who examined the food-unlimited growth rate of Atlantic cod under laboratory conditions. Older and larger cod have lower optimal temperatures for growth (Björnsson & Steinarsson 2002) and the local distribution of cod is known to depend on depth and temperature (Ottersen et al. 1998). Blanchard *et al.* (2005a) used information on optimal temperatures for growth and a model of habitat selection, 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. The combined negative effects of increased temperature on recruitment rates and the reduced availability of optimal habitat may have increased the vulnerability of the cod population to fishing mortality.

Larval and juvenile growth are very dependent on temperature. A study by Otterlei *et al.* (1999), whereby cod larvae and juveniles were reared in the laboratory, observed much faster growth when temperatures were increased from 4 to 14°C, corresponding with shorter larval stages. The temperature optimum of larval cod fed in excess was estimated at 14–16°C, and temperature and body condition were positively correlated (Otterlei *et al.* 1999). In the field, a positive link between temperature and larval growth has also been found, although there appears to be a stronger, positive link with **photoperiod** (Buckley *et al.* 2006). It is important to note however, that when food is scarce, higher temperatures might actually lead to decreased growth through higher metabolic costs, as demonstrated experimentally (Buckley *et al.* 2006).

In several cod stocks, marked changes in maturity have taken place, with fish now maturing at earlier ages and smaller sizes than they did some decades ago (north-east Arctic cod: Jørgensen 1990, Heino *et al.* 2002, 2004; Georges Bank and Gulf of Maine cod: O'Brien 1999, Barot *et al.* 2004; northern cod: Olsen *et al.* 2004). These changes have been attributed, partly, to fisheries-induced genetic selection for earlier maturation (evolutionary change). However, faster growth can also result from changing climatic conditions

directly influencing food abundance. Both processes are thought to have contributed to maturity changes in cod (Heino *et al.* 2002; Barot *et al.* 2004; Olsen *et al.* 2004).

Under natural conditions, where the food resources may be limited, or less predictable, optimal temperatures for growth are likely to be reduced (Despatie *et al.*, 2001). The situation is further complicated by a haemoglobin polymorphism in cod (Sick, 1961) that is expressed differently across the geographical distribution of the species (Jamieson & Birley, 1989). The haemoglobin polymorphism is correlated with mean annual sea temperatures in the wild (Sick, 1961), and is reflected by different temperature preferences in the laboratory (Petersen & Steffensen, 2003). Wild fish may select temperatures that are sub- or super-optimal relative to individuals in laboratory studies as a result of interactions with other species, including potential prey, predators and competitors (Ottersen *et al.*, 2004), and it is possible that laboratory studies describing the thermal ecology of cod (and other species) are not fully representative of wild fish.

Fisheries

Perry *et al.* (2005) demonstrated that distributions of both exploited and non-exploited North Sea fishes have changed markedly over the last 25 years. These authors suggest 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 impact upon commercial fisheries catches because changes in migration or spawning behaviour affect the 'catchability' of individuals to particular fishing gears. Populations may move away from (or towards) the area where fishing boats operate or where particular quotas or restrictions are in place (ICES 2007). Alternately, the animals may behave differently in response to the oncoming gear, behaving in a more sluggish or skittish manner and thus making them more or less vulnerable to capture (Winger 2005).

In North Sea plaice juvenile stages are concentrated in shallow inshore waters and move gradually offshore as they become larger. The nursery areas on the eastern side of the North Sea contribute most of the total recruitment. In recent years juvenile plaice have been distributed further offshore (Keeken *et al.*, 2007) than was the case previously. Surveys in the Wadden Sea have shown that 1-group plaice is almost absent from the area where it was very abundant in earlier years. This change in distribution has been suggested as one of the main reasons that the North Sea 'Plaice Box' has failed to be successful as a fishery conservation tool in the region. Environmentally induced changes in growth will also affect the catchability of fish, and thus discarding behaviour of fishing fleets (van Keeken *et al.*, 2003). Populations might also retreat into areas where they experience higher predation pressure, as was thought to have been the case in the 1980s, when the heavily depleted North Sea herring population contracted into the Norwegian Trench and experienced higher predation from saithe (Larsen & Gislason 1992).

Extensive fishing may cause fish populations to be more vulnerable to short-term natural climate variability (O'Brien *et al.,* 2000; Walther *et al.,* 2002; Beaugrand *et al.,* 2003), 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 (Jennings & Blanchard 2004).

During recent decades there has been a clear, positive correlation between temperature and recruitment in Northeast Artic cod, however this link was weak or non-existent in earlier periods (Ottersen & Stenseth 2001). 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, whereby spawners were on average 10–11 years old and >90 cm long in the past, compared to an average of 7–8 years old (or only 3 years old in the North Sea) and 80 cm long at present. The number of age classes has also decreased. This has been attributed to high fishing mortality especially from the 1960s onwards (Godø 2003; Ottersen *et al.* 2006) and to decreased age and size at maturation (Heino *et al.* 2002). A major implication is that a fishery-induced impoverishment of stock structure (reduced and fewer ages, smaller sizes) can increase the sensitivity of a previously 'robust' stock to climate change. Worryingly, truncations in the age distributions of spawners have occurred in most cod stocks.

As mentioned above, many traditional fishery target species such as cod and herring are anticipated to suffer poor recruitment, restricted growth and a northward distribution shift, away from UK waters in the near future. However it should be noted that fishermen and consumers may benefit from new opportunities, including the expansion of commercially exploitable warmer-water fish resources such as red mullet, John Dory, and seabass.

Red mullet is a non-quota species of moderate, but increasing, importance to fisheries. From about 1990, international landings from the English Channel increased strongly, and so have the landings from the North Sea. There are indications that red mullet have shown a northward distribution shift in recent years. Beare et al. (2004) demonstrated that red mullet are among several species with southern biogeographic affinities that have become significantly more prevalent in North Sea bottom trawl surveys.

John Dory is highly regarded as a food fish and is of commercial importance because of its high price in fish markets. Between 1980 and 2005, international landings of north-east Atlantic John dory quadrupled and in relative terms, the increase in landings appears more marked for "northerly" countries (UK and Ireland, 5- and 300-fold increase between 1980 and 2000, respectively) than for France (2.7-fold) and Portugal (1.3-fold). For the UK, Dunn (2001) examined trends in both quantities and values of the landings in more detail. Since 1980 the importance of exploitation of John dory has risen very significantly. Not only did total landings increase from 46 tonnes in 1980 to 148 t in 1997, but the

price experienced a steep increase, from £1.59 to £4.68 kg^{-1} (Dunn 2001). Heessen (1996) analysed time-series data from IBTS surveys for the period 1970–1993 and reported that John Dory was among 4 "southern" species that showed a remarkable increase in the southern North Sea. Beare *et al.* (2004) analysed a longer time-series (1925–2004) and confirmed that John Dory showed a similar, though smaller, peak in the warm 1950s.

Around England and Wales, sea bass are primarily exploited by commercial fishers using a variety of fishing methods in small boats close to shore and by recreational anglers. Pawson et al (2007) suggested that the stock biomass (SSB) of bass around the coasts of England and Wales generally increased between 1985 and 2004, although the pattern and magnitude of the increase differed between sub-regions. SSB in the English Channel quadrupled, from around 500 tonnes in 1985 to >2000 tonnes in 2003/2004, stocks in the Irish Sea and south-west appear to have followed a similar pattern. The North Sea spawning stock appears to have increased slightly from about 600 to 800 tonnes. However, other than in the Thames Estuary, there is as yet no tradition of commercial fishing for sea bass in the North Sea.

What we might expect in the future

Drinkwater (2005) reviewed the possible impacts 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.

Pörtner (2001) modelled the likely effects of future climate (*e.g.* temperature) on cod populations and predicted a northerly distribution shift. Their predictions also included increased growth rates and fecundity of cod in northern stocks, consistent with observations from the field. Clarke *et al* (2003) used projections of future North Sea surface temperatures and estimated the likely impact of future climate change on the reproductive capacity of the North Sea cod stock, assuming that the current high level of mortality inflicted by the fishing industry continues. Output from the model suggested that the cod population will decline, even without a significant temperature increase. However, even a relatively modest level of climate change (+0.005 °C yr^{-1}), resulted in a more rapid decline in fish biomass and juvenile recruitment. Scenarios with higher rates of temperature increase resulted in faster rates of decline in the cod population.

In the analyses of Clarke *et al* (2003), fishing mortality was assumed to continue at the 1998-2000 average (F = 0.96). This is a relatively high value

and does not take into account current efforts to cut fishing pressure. In a recent 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 SSB 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, climate change may have a greater effects on stock status, but higher yields and biomass might equally be expected (perhaps more so) if fishing mortality is reduced.

'Other' climate impacts on fish?

Since the 1970s, the frequency and spatial distribution of phytoplankton blooms and associated fish kills have been increasing in coastal seas throughout the world. Why such events are becoming more frequent remains a matter of conjecture, but eutrophication of the coastal zone by human activity, together with increasing global temperatures are often suspected. A recent study (Peperzak 2003; 2005) has attempted to evaluate whether harmful algal blooms are likely to occur more or less often over the next 100 years in the North Sea. Change in climate is expected to lead to an increase in extreme precipitation events (intense rainfall) in Britain, this will result in sudden pulses of freshwater being released at the coast and hence intermittent salinity stratification in an area immediately offshore. During such conditions, surface phytoplankton benefit from a decrease in salinity, greater availability of terrestrial nutrients, rapid increases in daily irradiance and higher water temperature, all of which are conducive to bloom formation. Increasing global temperature may also lead to faster growth rates, particularly for highly toxic phytoplankton varieties such as *Prorocentrum* (producers of shellfish toxins), *Chattonella* and *Fibrocapsa* (toxic to fish). *Gyrodinium* is harmless to humans but can cause mass-mortalities among fish. This dinoflagellate produces a potent neurotoxin, which is known to bioaccumulate in the zooplankton food-chain (Environment Agency 2004).

Most carbon dioxide released into the atmosphere as a result of burning fossil fuels will eventually be absorbed into the ocean. As the amount of CO_2 in the atmosphere rises, more of the gas reacts with seawater to produce bicarbonate and hydrogen ions, thereby increasing the acidity of the surface layer. A report published by the Royal Society in June 2005 suggested that higher concentrations of carbon dioxide may make it harder for some marine animals to obtain oxygen from seawater. Fish and the larger invertebrates including cephalopods such as squid, take up oxygen and lose respired CO_2 through their gills. Deep sea fish and cephalopods are known to be very sensitive to increases in external CO_2 and pH (Ishimatsu *et al.* 2004). We

have limited understanding of the effect increased acidity might have on marine biota, but organisms whose skeletons or shells contain calcium carbonate (e.g. crustaceans, corals etc.), may be particularly affected. Many such organisms are a major food source for fish and higher consumers.

Scientists believe that marine life is at growing risk from a range of diseases whose spread is being hastened by global warming, accelerated global transport by man and pollution (Harvell *et al.* 1999, 2002). They cite a number of well-documented cases such as Crab-eater seals in Antarctica infected with distemper by sled-dogs, and sardines in Australia infected with herpes virus caught from imported frozen pilchards. In the past few decades, there has been a worldwide increase in the reports of diseases affecting marine organisms. A disease outbreak is favoured by changing environmental conditions that either increase prevalence and virulence of an existing disease or facilitate the establishment. Climate variability and human activity appear to have played roles in epidemics by undermining host resistance and facilitating pathogen transmission (Harvell *et al.* 1999, 2002).

Important insights in 2006/2007

Since the publication of the 2006 MCCIP ARC, the link between climate – fish and fisheries has continued to receive considerable attention in both the national and specialist press (e.g. *Guardian* 18th July 2007, *Fishing News* 15th Dec 06, 13th Apr 07, 25th May 07, 29th June 07). Vagrant or occasional species have been reported all around the coasts of the UK, and there has been much discussion about possible shifts in species distribution, associated with warmer temperatures. Incidental records of pelagic vagrants (e.g derbio *Trachinotus ovatus*, bogue *Boops boops*, dealfish *Trachipterus arcticus*, Ray's bream *Brama brama*) have continued, as have reports of sailfin dory (*Zenopsis conchifera*), and Trigger fish - *Balistes capriscus* in the south-west.

The much-reported influx of snake pipefish (*Entelurus aequoreus*) into the waters of the British Isles has continued apace, with several authors now publishing on this phenomenon in the scientific literature (e.g. Harris *et al.* 2007; Kloppmann & Ulleweit 2007; Lindley *et al.* 2006; van Damme & Couperus 2006). It has been suggested that this influx might pose a threat to certain marine predators, notably seabirds (Harris *et al.* 2007), but they have also been reported as occurring in the stomach contents of important commercial fish species (Stafford *et al.* 2007), possibly associated with a lack of 'usual' prey types such as sandeels. Kirby *et al.* (2006) speculate that the increased abundance of larval and juvenile *E. aequoreus* in CPR plankton samples as far west as the Mid-Atlantic Ridge may coincide with a rise in winter, spring and summer sea temperatures (January–September), when the eggs, which are brooded by the male, are developing and the larvae are growing in the plankton. van Damme & Couperus (2006) put forward the alternative hypothesis that the sudden appearance of this species is a result of changes in zooplankton availability, which in turn has been caused by changes in the hydroclimatic environment.

Several research papers have emerged in 2006/2007 providing additional

insight into the relationship between cod (*Gadus morhua*) and changing climate in the North Sea although comparable data for other regions are still lacking (see Knowledge Gaps). 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 recent 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 superoptimal for growth. Cooler waters were 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.

By contrast, Rindorf & Lewey (2006) have argued that a series of winters characterized by high temperatures together with strong southerly winds (during the egg and larval phases) has led to an apparent northward shift in the distribution of juvenile cod. A concomitant northern shift of mature fish around the time of spawning was linked directly to a tendency for northerly distributed juveniles to remain northerly throughout their life. This shift to an overall northward shift in the centre of gravity of the species, supporting the contention of Perry *et al*. (2005) (although see 'Disentangling the effects of fisheries and climate' section above).

Pilling *et al.* (2007) reported a change in the timing of otolith (fish ear bone) annulus formation in North Sea cod, during warm versus cold periods (1985-1986 contrasted against 1994-1995). Specifically, translucent zone formation in otoliths was found to begin earlier during the warmer period, corresponding to peak annual sea surface temperatures, and a period of slow body growth and low metabolic activity. 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.

Another high-profile research paper which emerged in 2007 (Pörtner & Knust 2007) focused on the eelpout *Zoarces viviparous*. This study (drawing on laboratory experiments) suggested that a mismatch exists between the demand for oxygen and the capacity to supply oxygen to tissues when fish are under thermal stress. Thermally-limited oxygen delivery was associated with environmental temperatures beyond which growth performance was impaired. Hence, the authors concluded that decrements in aerobic performance in warming seas will be an important process leading to extinction or relocation of species to cooler waters.

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 rather than NAO and productivity. 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.

Several very useful review papers have been published in 2006/2007 most notably that written by Harrod *et al.* on behalf of the Fisheries Society of the British Isles (FSBI 2007). This review attempts to describe the possible implications of climate change for freshwater, **diadromous** and marine fishes. It provides a detailed species-by-species summary for UK waters, and an overview of predicted future changes in the physical environment. Heath (2007) also reviewed the literature discussing fish and climate change in European waters, placing particular emphasis on changing distribution patterns.

Lehodey *et al.* (2006) provided a useful overview drawing on the wealth of experience gained through the international GLOBEC (Global Ocean Ecosystems Dynamics) programme. This paper provides examples of relationships between climate variability and fisheries at a range of different time scales for species inhabiting marine ecosystems ranging from equatorial to subarctic regions. Some of the known mechanisms linking climate variability and exploited fish populations are described, as well as leading hypotheses, implications for management and for modelling.

Confidence Assessments

Fish
'What is already happening' – Medium
'What could happen in the future' – Low

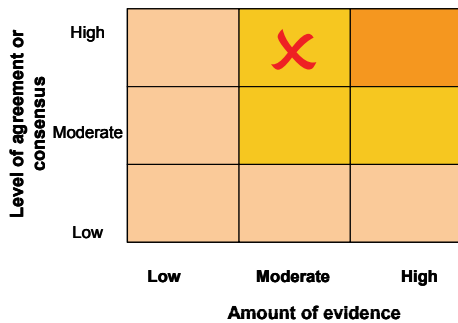*Fisheries*
'What is already happening' – Medium
'What could happen in the future' – Medium

For cod, plaice and sole in the North Sea, where there are extensive data and many published analyses, we can say with high confidence that climate change has compromised the ability of the stock to withstand fishing mortality. Fishing mortality rates, which were considered sustainable 30 years ago, are now unsustainable due to negative effects 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 in UK waters (herring, mackerel, haddock, saithe, whiting, monkfish) we have only medium or low confidence

in the effects of climate change. This may be partly because a variety of other factors obscure any relationships with temperature, or simply because of a lack of adequate data.

Much less is known regarding the likely responses of non-commercial species to marine climate change, largely because of the lack of data spanning sufficient time interval to analyse changes. 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.
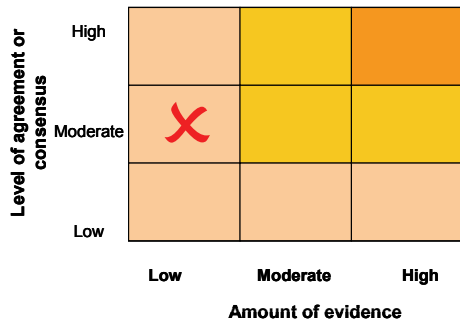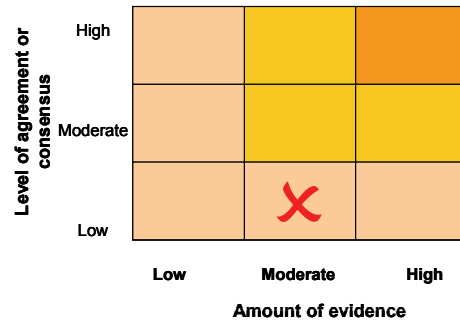
Fish: happening now

Fisheries: happening now
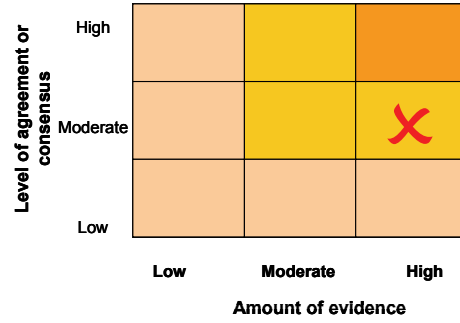
Fish: in the future

Fisheries: in the future

Knowledge gaps

Most of our conclusions regarding the response of fish and fisheries to climate change are assembled from fragmentary information from surveys, fishery landings, anglers and other observers. Despite scientific study we are still not sure exactly why, for example, sea temperature has a negative effect on cod recruitment. However, recent studies using data storage tags, genetics and analyses of **otolith** microstructure and chemistry have begun to unravel the behavioral and physiological processes that dictate the distribution and production of cod in the North Sea. These types of study seem to offer the most promising way of diagnosing the reactions of fish to changing climate conditions in sufficient detail for us to be able to predict responses in the future.

Where data is lacking:

- ‘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, attempting to estimate changes in fish distributions, interactions between fish species as a result of changing distributions, the ecological role of incoming species, prospects for stock recovery and rebuilding.
- Experimental studies relating growth and reproductive output (in species other than cod) to temperature and/or other environmental variables.
- Information on how the behaviour of commercial fish species might be impacted by climatic changes, and thus the impact of climate variability on 'catchability' by fishing fleets.

Commercial impacts

The major commercial impact of climate change on fisheries has been to reduce the maximum sustainable yield of various historically important species, in particular cod, plaice and sole in the North Sea. In the case of cod, climate change has been estimated to have been eroding the maximum sustainable yield at a rate of 32,000 t per decade since 1980. Even if current stock rebuilding measures are effective, it cannot be expected that the fishery could be restored to its past state. Conversely, it seems likely that in the future, significant new fisheries will develop for species, which were not traditionally caught in UK waters, though it is hard to predict what these might be at present.

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What long-term data sets are available?

- Stock recruitment indices for all major commercial fish stocks. Available from ICES stock assessments (www.ices.dk). Also stock biomass and numbers.
- Fish stock abundance estimates from scientific surveys (both commercial and non-commercial species) from ICES and national laboratories (including FRS, AFBI and Cefas).
- Small-scale, long-term scientific surveys of local fish populations (e.g. for the area around Plymouth).
- Fish captured on power station intake screens (e.g. Attrill & Power 2002; Henderson 2007).
- Numbers of fish eggs and larvae – available (but not worked-up in recent years) as part of annual CPR (Continuous Plankton Recorder) programme. Supplemented with recent systematic surveys of fish eggs and larvae in the North Sea (C. Fox, pers. Comm.; Greve et al. 2005), Celtic and Irish Seas (e.g. Fives 2001).
- Studies/data-sets of fish larval diets (e.g. Shaw *et al.* 2006; Last 1978a,b; 1980).

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