12 Socio-economic Impacts—Fisheries

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Abstract

Fishers and scientists have known for over 100 years that the status of fish stocks can be greatly influenced by prevailing climatic conditions. Based on historical sea surface temperature data, the North Sea has been identified as one of 20 'hot spots' of climate change globally and projections for the next 100 years suggest that the region will continue to warm. The consequences of this rapid temperature rise are already being seen in shifts in species distribution and variability in stock recruitment. This chapter reviews current evidence for climate change effects on fisheries in the North Sea—one of the most important fishing grounds in the world—as well as available projections for North Sea fisheries in the future. Discussion focuses on biological, operational and wider market concerns, as well as on possible economic consequences. It is clear that fish communities and the fisheries that target them will be very different in 50 or 100 years' time and that management and governance will need to adapt accordingly.

12.1 Introduction

The North Sea remains one of the world's most important fishing grounds. In 2013, around 3.5 million tonnes of fish and shellfish were taken from the region (2.6 million tonnes by EU countries), approximately 55 % of the total for EU countries as a whole. European fisheries are very diverse, ranging from highly industrialised distant-water fisheries to small-scale artisanal fisheries that typically operate near the coast. EU citizens consume large quantities of seafood each year (currently around 23.3 kg on average per person), and rely on fisheries for health and well-being, as well as for supporting more than 120,000 jobs directly and a further 115,000 in fish processing (STECF 2013). There has been

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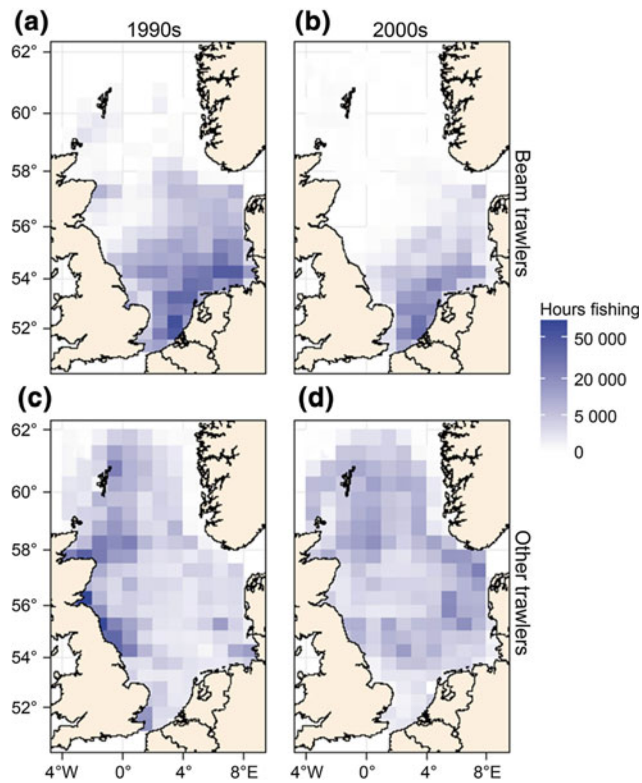

Fig. 12.1 Spatial distribution of international fishing effort in the North Sea by beam trawlers (*upper*) and demersal otter trawlers (*lower*), averaged by year over the periods 1990–1995 (*left*) and 2003–2012 (*right*). *Light to dark shading* indicates the number of hours fishing in each ICES rectangle (redrawn from Engelhard et al. 2015)

much debate in the literature with regard to the extent to which fisheries might be sensitive to climate change and a number of national-scale assessments have been conducted, for example for the United Kingdom (Cheung et al. 2012; Pinnegar et al. 2013). To date, however, no North Sea-wide assessment of climate impacts on the fisheries sector has been carried out and there is limited information for many countries despite the wide-scale and well-documented implications.

12.2 Overview of North Sea Fisheries

Commercial fishing activity in the North Sea is mostly undertaken by fishers from the UK (England and Scotland), Denmark, the Netherlands, France, Germany, Belgium and Norway (Fig. 12.1). Total fish removals are dominated by pelagic species (those that swim in the water column, above the seabed) such as herring *Clupea harengus* (986,471 tonnes), sprat *Sprattus sprattus* (143,581 tonnes), and mackerel *Scomber scombrus* (644,762 tonnes), although demersal fishes are also important. Demersal fish are those that live close to the sea floor and are typically caught by 'otter trawlers'. The most important demersal species include Atlantic cod *Gadus morhua*, haddock *Melanogrammus aeglefinus* and whiting *Merlangius merlangus*, although a wide variety of other species such as saithe *Pollachius virens* and monkfish *Lophius piscatorius* are also caught. Total demersal fishing effort has decreased dramatically over the past 10 years. The estimated overall reduction in effort (kW days at sea) by 2013 amounted to 43 % compared to the average for 2004–2006. Most landings in the demersal otter-trawl fishing sector are taken from the northern North Sea (Fig. 12.1) and the fishery is overwhelmingly dominated by Danish, UK, Norwegian and German vessels.

Major *Nephrops norvegicus* (langoustine) grounds in the North Sea include the Flåden Ground, the Farne Deeps (NE England), Botany Gut (central North Sea) and Horns Reef (west of Denmark). Landings of *Nephrops* have increased in recent years, from 10,613 tonnes in 1990 to a maximum of 90,996 tonnes in 2010, and this reflects restrictions on gear types with larger mesh-size, targeting demersal white-fish.

The North Sea beam trawl fishery mainly targets flatfish (sole *Solea solea* and plaice *Pleuronectes platessa*), but is also known to catch cod, whiting and dab *Limanda limanda*. The average distribution of fishing effort in this sector is illustrated in Fig. 12.1 which suggests that beam trawlers typically operate in the southern North Sea. The Dutch beam trawl fleet is the major player in the mixed flatfish fishery, although Belgian and UK-flagged vessels also operate in this fishery. Total fishing effort by the North Sea beam trawl fleet has reduced by 65 % over the last 15 years and there has also been a shift towards electronic pulse trawls more recently (ICES 2014a).

Fisheries for herring use midwater trawl gears (50–55 mm mesh) and target discrete shoals of fish that are located using echosounding equipment. There is also a purse-seine fishery for herring in the eastern North Sea (Dickey-Collas et al. 2013). The stock is fished throughout the year, with peak catches between October and March. Landings of herring in the autumn are predominantly taken from Orkney and Shetland, off Peterhead, northwest of the Dogger Bank and from coastal waters off eastern England. Landings in the spring are concentrated in the south-western North Sea.

The North Sea is subject to major industrial fisheries targeting sandeel *Ammodytes marinus*, Norway pout *Trisopterus esmarkii*, blue whiting *Micromesistius poutassou*, sprat, and juvenile herring. These fish are mainly caught on offshore sand-banks using fine-meshed (8–32 mm) midwater trawls (Dickey-Collas et al. 2013). The sandeel fishery was the largest single-species fishery in Europe with peak landings in 1997 exceeding 1 million tonnes. The fleet has since declined in size. Total sandeel landings in 2013 were 529,141 tonnes (15 % of total landings), Norway pout

Table 12.1 Factors related to the North Sea fishing industry that could be affected by climate change

Biology—Fish and shellfish	Fishery operations	Fish markets and commodity chains
• Year-class strength (recruitment) • Migration patterns • Distribution/habitat suitability • Growth rate • 'Scope for growth' and energetic balance • Phenology (timing of spawning etc.) • Activity levels • Prey availability (match/mismatch) • Exposure to predators • Pathogen and pest incidence • Calcification and internal carbonate balance (shellfish) • Damage/disturbance of key nursery/spawning habitats	• Catchability (performance of the fishing gear) • Vessel safety and stability (e.g. storminess) • Fuel usage (to follow the shifting fish) • Restrictive TACs and quotas (EU relative stability arrangements) • Effectiveness of spatial closures in protecting spawning/nursery areas • New resource species, requiring new fishing gears • Storm damage to ports, harbours and onshore facilities • Damage to gear and vessels (e.g. storm damage to fixed gears) • Preservation of catch on-board vessels • Fouling of vessel hulls • Unwanted 'choke species' that constrain fishing operations	• New markets for novel species • Demand for fish (nationally and internationally) • Storm damage to processing facilities on land • Storm/flooding disruption to transport routes to market • Availability of alternative resources (nationally and internationally) including imports • Changes in processing requirements • Stability of incomes for fishermen and processors • Quality/robustness of product (e.g. shellfish)

landings were 155,752 tonnes (4 %) and blue whiting 17,645 tonnes (0.5 %). All of these short-lived industrial species are thought to be heavily influenced by climatic variability (e.g. Arnott and Ruxton 2002; Hátún et al. 2009).

12.3 Climate Change and Fisheries

There can be many different manifestations of climate change. The most noticeable effect is an increase in average seawater temperature over time, but the seasonality of warming and cooling is also expected to change. The North Sea has witnessed significant warming over the past century at a rate of around 0.3 °C per decade (Mackenzie and Schiedek 2007). The region has been identified as one of 20 'hot spots' of climate change globally, i.e. discrete marine areas where ocean warming has been fastest, as quantified from historical sea surface temperature data (Hobday and Pecl 2014). Projections suggest that the region will continue to experience warming, by around 2–3 °C over the next 100 years (Lowe et al. 2009). Climate change can also encompass other environmental influences or parameters such as changes in precipitation and run-off (and hence salinity and stratification), and storm frequency and intensity (Woolf and Wolf 2013) that may in-turn greatly impact fishing operations, and changes in chemical conditions such as dissolved oxygen concentrations, carbonate chemistry and seawater pH (Blackford and Gilbert 2007).

In this overview of climate change impacts on North Sea fisheries, all of these climatic influences are considered. Climate change will have consequences not only for the animals supporting fisheries (biological responses—see Table 12.1) but also direct and indirect implications for fishery operations—such as storm damage to gear, vessels and infrastructure, changes in catchability of species and maladaptation of quota allocation, etc. (Table 12.1). Furthermore, climate change elsewhere in the world can have consequences for the fishing industry closer to home, via globalised fish markets and commodity chains.

The following sections outline available evidence for climate change effects on fisheries in the North Sea as well as available projections for North Sea fisheries in the future. This assessment is based on Table 12.1, with a discussion of biological, operational and wider market concerns, including analyses of possible economic implications.

12.3.1 Biological Responses

12.3.1.1 Changes in Fish and Fishery Distribution

Long-term changes in seawater temperature and/or other ocean variables often coincide with observed changes in fish distribution. In an analysis of 50 fish species common in waters of the Northeast Atlantic, 70 % had responded to warming by changing distribution and abundance (Simpson et al. 2011). Specifically, warm-water species with smaller maximum body size had increased in abundance throughout northwest Europe while cold-water, large-bodied species had decreased in abundance.

Distribution and abundance are the traits that are the most readily observed responses. However, many processes interact when considering fisheries and climate change, and these are a manifestation of both biological and human processes. None of these factors act in isolation and many are synergistic. The responses are rarely linear. In fish, it is clear that climate affects physiology and behaviour. These processes interact to influence migration, productivity (growth of populations minus decline in populations), susceptibility to disease and interactions with other organisms. Changes in distribution and abundance are the aggregate responses to these changed processes.

Archaeological evidence can sometimes yield useful insights into historical changes in the distribution and productivity of fish and the response of fisheries. The bones of warm-water species such as red mullet *Mullus surmuletus* have been recovered from archaeological excavations throughout northern Europe. This species has only recently returned to the North Sea in reasonable numbers (Beare et al. 2005), but was apparently widespread during the Roman period (AD 64–400) (Barrett et al. 2004). Enghoff et al. (2007) listed a number of occurrences of warm-water species (e.g. red mullet, seabass *Dicentrarchus labrax*, anchovy *Engraulis encrasicolus*, and seabream *Spondyliosoma cantharus*) among bone assemblages, surrounding the North Sea, from the 1st to the 16th century AD. Alheit and Hagen (1997) identified nine periods, each lasting several decades, during which large quantities of herring were caught close to the shore in the North Sea. Each of these coincided with severe winters in western Europe with extremely cold air and water temperatures and a reduction in westerly winds; physical factors associated with negative anomalies of the North Atlantic Oscillation (NAO) index.

Highly-cited studies using time-series from fishery-independent surveys (Beare et al. 2004a; Perry et al. 2005; Dulvy et al. 2008) have revealed that centres of fish distribution in the North Sea shifted by distances ranging from 48 to 403 km during the period 1977–2001, and that the North Sea demersal fish assemblage has deepened by about 3.6 m per decade over the past 30 years (Dulvy et al. 2008). Species richness increased from 1985 to 2006 which Hiddink and Ter Hofstede (2008) suggested was related to climate change. Eight times as many fish species displayed increased distribution ranges in the North Sea (mainly small-sized species of southerly origin) compared to those whose range decreased (primarily large and northerly species). For a more localised region of the Dutch coast, van Hal et al. (2014) demonstrated latitudinal range shifts and changes in abundance of two non-commercial North Sea fish species, solenette *Buglossidium luteum* and scaldfish *Arnoglossus laterna* that were strongly related to the warming of the coastal waters. For pelagic fish species, a recent paper by Montero-Serra et al. (2015) investigated the patterns of species-level change using records from 57,870 fisheries-independent survey trawls from across the European continental shelf between 1965 and 2012. These authors noted a strong ‘subtropicalisation’ of the North Sea as well as the Baltic Sea. In both areas, there has been a shift from cold-water assemblages typically characterised by Atlantic herring and sprat from the 1960s to 1980s, to warmer-water assemblages typified by mackerel, horse mackerel *Trachurus trachurus*, sardine *Sardina pilchardus* and anchovy from the 1990s onwards. The primary measure correlated to changes in all species was sea surface temperature (Montero-Serra et al. 2015).

Analyses of Scottish and English commercial catch data in the North Sea spanning the period 1913–2007 have revealed that the locations where peak catches of target species such as cod, haddock, plaice and sole were obtained have all shifted over the past 100 years, albeit not in a consistent way (Engelhard et al. 2011, 2014b). For example, catches of cod seem to have shifted steadily north-eastward and towards deeper water in the North Sea (Engelhard et al. 2014b) and this reflects both climatic influences and intensive fishing. Plaice distribution has shifted north-westwards (Fig. 12.2) towards the central North Sea, again reflecting climatic influences, in particular sea surface temperature as also confirmed by van Keeken et al. (2007). Somewhat confusingly, sole seems to have retreated away from the Dutch coast, southwards towards the eastern Channel although this too is thought to have been a response to warming. Sole is a warm-water species that traditionally moved offshore in winter to avoid excessively low temperatures in the shallows. Cold winters are known to have coincided with mass die-offs of sole (e.g. Woodhead 1964), but in recent years shallower waters surrounding the North Sea have remained habitable all year round (winter conditions are less severe), and hence the apparent southward and shallowing shift (Engelhard et al. 2011). Haddock catches have moved very little in terms of their centre of distribution, but their southern boundary has shifted northwards by approximately 130 km over the past 80–90 years (Skinner 2009).

Theoretically, in the northern hemisphere, warming results in a distributional shift northward, and cooling draws species southward (Burrows et al. 2007). Heath (2007) looked at patterns in international fisheries landings for the whole Northeast Atlantic region. Densities of landings of each species were summed by decade and expressed as a proportion of the total. Both northerly and southerly shifts were observed between decades for individual species, however more species shifted south than north between the 1970s and 1980s (a relatively cool period) and vice versa between the 1980s and 1990s (a relatively warm period). This seems to parallel observed inter-decadal changes in sea and air temperatures.

Distribution shifts will have ‘knock on’ implications for commercial fisheries catches because changes in migration or spawning location affect the ‘availability’ of resources to fishing fleets. Populations may move away from or towards the area where particular fishing fleets operate and/or where spatial restrictions on fishing are in place. Furthermore, species distributions may migrate across political boundaries where quotas belong to different nations. A notable example has arisen recently as a result of quota allocations between

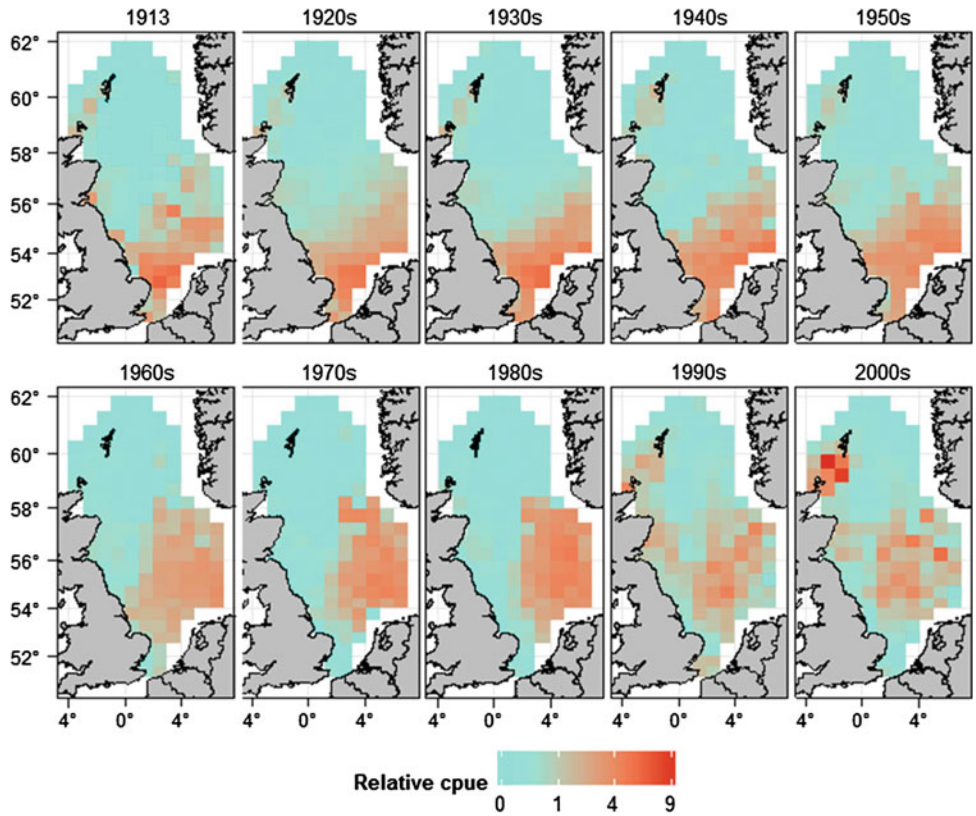

Fig. 12.2 Decadal change in North Sea plaice distribution, 1920s to 2000s, based on fisheries catch-per-unit-effort (CPUE). Shading is proportional to plaice CPUE, normalised by decade and corrected for the average spawning stock biomass (SSB). Adapted from Engelhard et al. (2011)

Norway and the EU, and between Iceland, the Faroe Islands and the EU. In October 2009, North Sea mackerel appeared to have moved away from the Norwegian Sector (possibly as a result of excessively cold conditions near the Norwegian coast), resulting in disagreements over permissible catches by Norwegian boats in EU waters. Norwegian vessels were forcibly evicted by UK fishery patrol vessels, once they had caught their allotted quota (see *Fishing News*, 9 October 2009). At the same time Iceland and the Faroe Islands unilaterally claimed quota for mackerel (146,000 and 150,000 tonnes respectively in 2011 or 46 % of the total allowable catch, TAC), since the species had suddenly attained high abundance in their territorial waters. Whether the apparent changes in mackerel distribution westwards across the northern North Sea were a result of long-term climate change or not remains unclear. Hughes et al. (2014) suggested that sea surface temperature had a significant positive association with the observed northward and westward movement of mackerel, equivalent to a displacement of 37.7 km per °C (based on spring mean sea surface temperature for the region). By contrast, historical appearances of mackerel in the western North Sea and off the coast of Iceland (Beare et al. 2004a) coincided with warming periods linked to the Atlantic Multidecadal Oscillation (AMO) and might not be symptomatic of long-term climate change. Whatever the case—with climate change in the future, more territorial disagreements of this type could be anticipated (Hannesson 2007) and fisheries management will need to adapt accordingly (Link et al. 2011).

A similar phenomenon is now occurring in the English Channel and southern North Sea region with regard to access to European anchovy. Anchovy stocks are currently depleted in the Bay of Biscay where Spanish and French vessels operate, but are increasing further north along southern coasts of the UK and especially along Dutch coasts (Beare et al. 2004b) where they are starting to be targeted by pelagic fishing vessels. Detailed political negotiations are underway to determine whether Spanish and French vessels should be allowed exclusive access in areas where previously they had no quota, and indeed whether the more northerly distributed anchovy represent the same or a genetically different sub-stock to those in the Bay of Biscay. In 2012 a study was published (Petitgas et al. 2012) drawing on four different strands of evidence: genetic studies, larval transport modelling, survey time series and physical oceanographic models. The study concluded that anchovy in the southern North Sea are most likely to be a distinct remnant sub-stock that was previously present (see Aurich 1953), but is now benefiting from greatly improved climatic conditions rather than an invasion of animals from further south. According to

Alheit et al. (2012), the anchovy population from the western Channel (not from the Bay of Biscay) invaded the North Sea and Baltic Sea during positive periods of the AMO. Given this evidence and according to the rules of 'relative stability' within the EU Common Fisheries Policy, Spanish and French vessels would not necessarily be granted exclusive access to this expanding resource, unlike the present situation in the Bay of Biscay.

Under the EU Common Fisheries Policy, a number of closed areas have been implemented as 'technical measures' to conserve particular species and to protect nursery or spawning grounds. In the North Sea, these include closure areas to protect plaice, herring, Norway pout and sandeel. If species shift their distribution in response to climate change then it is possible that such measures will become less effective in the future (van Keeken et al. 2007). Juvenile plaice are typically concentrated in shallow inshore waters of the southeast North Sea and move gradually offshore as they grow. In order to reduce discarding of undersized plaice, thereby decreasing mortality and enhancing recruitment to the fishery, the EU 'Plaice Box' was introduced in 1989, excluding access to beam and otter trawlers larger than 300 hp. However recent surveys in the Wadden Sea have shown that 1-group plaice are now completely absent from the area where they were once very abundant. Consequently, the 'Plaice Box' is now less effective as a management measure for plaice than was the case 10 or 15 years ago. The boundaries of, and expected benefits from marine protected areas (MPAs) may need to be 'adaptive' in the future in the context of climate change. Cheung et al. (2012) looked at other fishery closure areas in the North Sea and noted that they will most likely experience between 2 and 3 °C increases in temperature over the next 80–100 years and consequently it is unlikely that the species they are designed to protect now will occur there in the same numbers in the future given defined temperature tolerances or preferences of specific fishes (Freitas et al. 2007; Pörtner and Peck 2010).

Fishers have witnessed and responded to a number of new opportunities in recent years, as warm-water species have moved into the North Sea and/or their exploitation has become commercially viable for the first time. Notable examples include new or expanding fisheries for seabass, red mullet, John dory *Zeus faber*, anchovy and squid *Loligo forbesi*.

Biomass estimates for seabass in the eastern Channel quadrupled from around 500 tonnes in 1985, to in excess of 2100 tonnes in 2004/2005, with populations also increasing rapidly in the southern North Sea (Pawson et al. 2007). This was attributed to an increase in seawater temperature, especially in the winter and has resulted in a dramatic expansion of seabass fisheries both within the commercial sector and the recreational fishing sector. Seabass are caught by angling on the east coast of Scotland and in Norway, but the northernmost limit of the commercial seabass fishery is around Yorkshire (54°N) in the North Sea. In 2013, 2243 tonnes of seabass were landed by countries surrounding the North Sea and eastern English Channel (Fig. 12.3), compared with only 210 tonnes in 1990. However recent anecdotal evidence (ICES 2012) seems to suggest that the increase in catches may have slowed slightly, as a result of successive cold winters in 2009/10, 2010/11, and 2011/12 likely leading to poor recruitment (Fig. 12.3).

Red mullet is a non-quota species of moderate, but increasing, importance to North Sea fisheries. From 1990 onwards, international landings increased strongly. France is the main country targeting this species although UK and Dutch commercial catches have also increased. Total international landings rose from only 537 tonnes in 1990 to a peak in landings of 4555 tonnes in 2007. Beare et al. (2005) demonstrated that red mullet is one of many species that have become significantly more prevalent in North Sea bottom trawl surveys in recent years, rising from near-absence during surveys between 1925 and 1990, to about 0.1–4 fish per hour of trawling between 1994 and 2004. Red mullet is also among the fish species that have entered the North Sea from both the south and north-west, through the Channel and along the Scottish coast, respectively (Beare et al. 2005).

Although numbers are highly uncertain, there are strong indications that squid are generally becoming more abundant in the North Sea, possibly in response to a change in climate (Hastie et al. 2009a). Cephalopod populations are suggested to be highly responsive to climate change (Sims et al. 2001; Hastie et al. 2009a) and growth in squid availability in the North Sea is generating considerable interest among fishers off the Scottish coast (Hastie et al. 2009b). Off north-east Scotland, where most of the squid are found, more boats are now trawling for squid than for the region's traditional target species, such as haddock and cod (Hastie et al. 2009b). New squid fisheries are also emerging in the Netherlands using bright lamps and hooked lines (*Fish News* September 2007). Total international landings have risen from 2612 tonnes in 1990 (375 tonnes in 1980) to 3417 tonnes in 2013 (see Fig. 12.3). In the English Channel, loliginid squid catches seem to be related to mean sea surface temperature (Robin and Denis 1999). Temperature appears to influence recruitment strength and overall distribution (Hastie et al. 2009a).

The North Sea bottom trawl fleet typically catches many different species in the same haul, thus making it virtually impossible to devise effective management measures that are well suited to the protection or rebuilding of any particular stock without affecting others. In October 2014, the EU introduced reforms to the Common Fisheries Policy that included a ban on discarding and thus a requirement to land all fish caught. To allow fishers to adapt to the change, the landing obligation will be introduced gradually, between

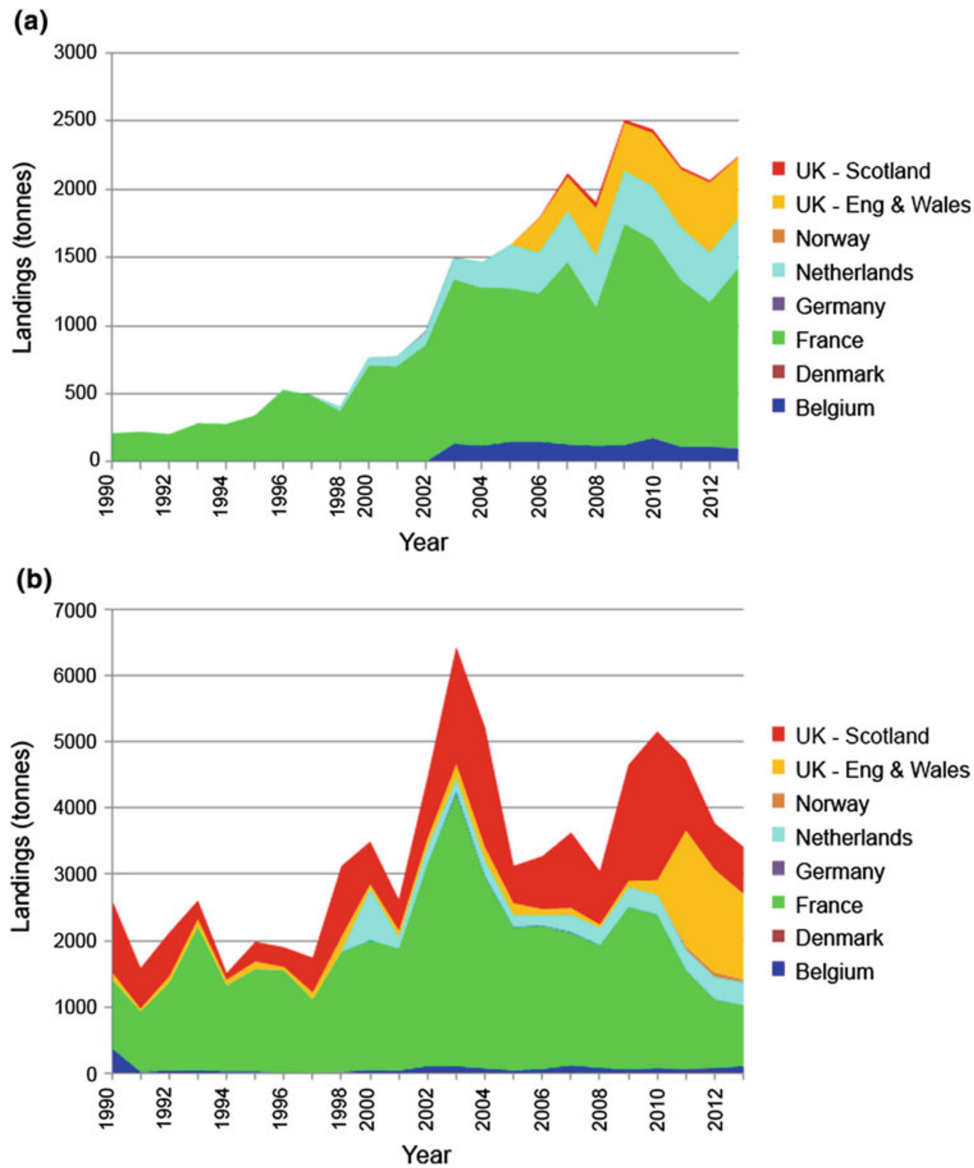

Fig. 12.3 International fishery landings of seabass (*upper*) and squid (*lower*) in the North Sea and eastern English Channel (data for 1999 were excluded as no French data were submitted to ICES in that year)

2015 and 2019 for all commercial fisheries (species under TACs, or under minimum sizes), however this new measure necessitates that once the least plentiful quota species in a mixed fishery—the 'choke species'—is exhausted, the whole fishery must cease operation. Baudron and Fernandez (2015) have argued that many commercial fish stocks are beginning to recover under more sustainable exploitation regimes and, in some cases, as a result of favourable climatic conditions. For example, northern European hake *Merluccius merluccius* a warm-water species, witnessed a dramatic increase in biomass between 2004 and 2011 and has recolonised the northern North Sea where hake had largely been absent for over 50 years. These changes have implications for the management of other stocks. Notably, if discards are banned as part of management revisions, the relatively low quota for hake in the North Sea will be a limiting factor (the so-called 'choke' species) which may result in a premature closure of the entire demersal mixed fishery (Baudron and Fernandez 2015).

Modelling strategies for predicting the potential impacts of climate change on the natural distribution of species and consequently the response of fisheries have often focused on the characterisation of a species' 'bioclimate envelope' (Pearson and Dawson 2003). In other words, by looking at the current range of temperatures inhabited by a species, it is possible to predict future distribution, on the basis that the physical environment in an area is likely to change in the future. Model simulations suggest that distributions of exploited species will continue to shift in the next five decades both globally and in the Northeast Atlantic specifically (Cheung et al. 2009, 2010, 2011; Lindegren et al. 2010).

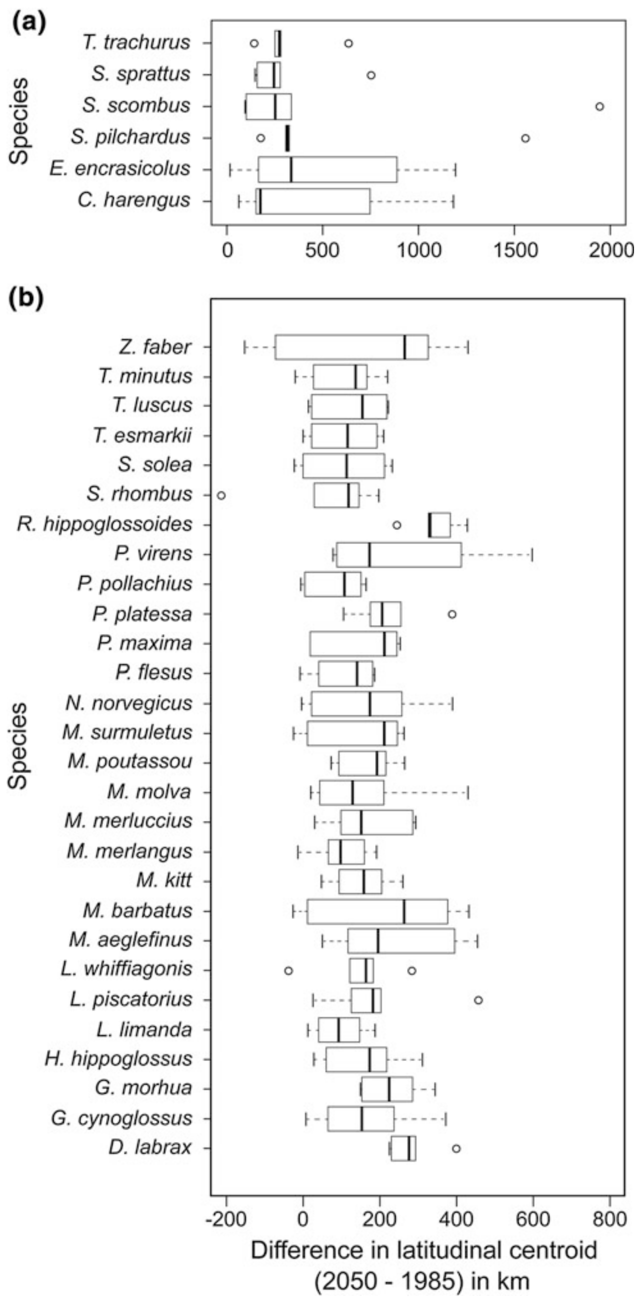

Fig. 12.4 Projected change in latitudinal centroids of habitat suitability surfaces from 1985 to 2050 across species distribution models and climatic datasets for pelagic species (*upper*) and demersal species (*lower*) (Defra 2013). *Thick vertical lines* represent median values, the left and right ends of each *box* show the upper and lower quartiles of the data and the whiskers the most extreme data points no greater than 1.5 times the inter-quartile range. Outliers that were more extreme than whiskers are represented as *circles*

It is important to test the reliability and robustness of tools projecting climate-driven shifts in fisheries resources. Jones et al. (2012) published a localised analysis for the North Sea and Northeast Atlantic whereby three different bioclimate envelope models (AquaMaps, Maxent and DBEM) were applied to the same present distribution datasets and the same environmental input parameters. As indicated by the test statistics, each method produced a plausible present distribution and estimate of habitats suitable for each species (14 commercial fish). When used to make projections into the future, the ensemble of models suggested northward shifts at an average rate of 27 km per decade (the current rate is around 20 km per decade for common fish in the North Sea, Dulvy et al. 2008). This modelling approach was extended to include several additional, commercial species (squid *Loligo vulgaris*, seabass, sardine, sprat, John dory, anchovy, plaice, herring, mackerel, halibut *Hippoglossus hippoglossus*, red mullet etc.) as part of a Defra study (Defra 2013). The species predicted to move the furthest were anchovy, sardine, Greenland halibut, John dory and seabass (i.e. *E. encrasicolus*, *S. pilchardus*, *R. hippoglossoides*, *Z. faber* and *D. labrax* respectively, see Fig. 12.4).

By contrast Rutterford et al. (2015) used the same fish survey datasets for the North Sea, together with generalised additive models (GAMs), to predict trends in the future distribution of species, but came to the conclusion that fish species over the next 50 years will be strongly constrained by the availability of suitable habitat in the North Sea, especially in terms of preferred depths. The authors found no consistent pattern among species in predicted changes in distribution. On the basis of the GAM results the authors suggested that they did not expect or predict substantial further deepening (as previously observed by Dulvy et al. 2008), and that the capacity of fish to remain in cooler water by changing their depth distribution had been largely exhausted by the 1980s, that fish with preferences for cooler water are being increasingly exposed to higher temperatures, with expected physiological, life history and negative population consequences.

Beaugrand et al. (2011) described a model to map the future spatial distribution of Atlantic cod. The model, which they named the non-parametric probabilistic ecological niche model (NPPEN), suggested that cod may eventually disappear as a commercial species from some regions including the North Sea where a sustained decline has already been documented; in contrast, the abundance of cod is likely to increase in the Barents Sea. Lenoir et al. (2011) applied the same NPPEN model with multiple explanatory variables (sea surface temperature, salinity, and bathymetry) to predict the distribution of eight fish species up to the 2090s for the Northeast Atlantic. This study anticipated that by the 2090s horse mackerel and anchovy would show an increased probability of occurrence in northern waters compared with the 1960s, that pollack *Pollachius pollachius*, haddock and saithe would show a decrease in the south, and that turbot *Scophthalmus maximus* and sprat would show no overall change in probability (−0.2 to +0.2) anywhere.

French scientists from IFREMER 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 and Loots 2009). Abundance of each species was related to depth, sediment type, bottom salinity and temperature. Results suggested that climate change may strongly affect the future distribution of plaice. For large plaice (>18 cm), 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 (as has already been observed, see van Keeken et al. 2007; Engelhard et al. 2011). Model outputs indicate that the distribution of red mullet will not change dramatically but that for young individuals (defined as <17.3 cm), the offshore habitat situated on the Dogger Bank may become increasingly favourable. Older individuals seemed little affected by the simulated change in environment, but they may benefit from higher juvenile survival and expand their area of occupation as a result.

There are some concerns about the validity of the bioclimate envelope approach for predicting the future distribution of commercially important fish species (see Jennings and Brander 2010; Heath et al. 2012). 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 land) and species will move at different rates and encounter different local ecologies as temperature changes (Davis et al. 1998). A more detailed, physiologically-based approach has been taken by some authors, whereby the detailed dynamics of individual animals are modelled, often by linking complex biophysical models (forced with the output from Global Climate Models) to sub-routines which replicate the behaviour/characteristics of eggs, larvae, juveniles or adults. Teal et al. (2008) reported a study of plaice and sole distribution in the North Sea, in which they predicted size- and season-specific fish distributions based on the physiology of the species, temperature and food conditions in the sea. This study combined state-of-the-art dynamic energy budget (DEB) models with output from a biogeochemical ecosystem model (ERSEM) forced with observed climatic data for 1989 and 2002, with contrasting temperature and food conditions. The resulting habitat quality maps were in broad agreement with observed ontogenetic and seasonal changes in distribution as well as with long-term observed changes in distribution. The technique has recently been extended to provide future projections up to year 2050, assuming moderate climate warming (L. Teal, pers. comm. IMARES, Netherlands).

12.3.1.2 Year-Class Strength and Implications for Fisheries

Fishers and scientists have known for over 100 years that the status of fish stocks can be greatly influenced by prevailing climatic conditions (Hjort 1914; Cushing 1982). ‘Recruitment’ variability is a key measure of stock productivity, and is defined as the number of juvenile fish surviving from the annual egg production to be exploited by the fishery. Recruitment is critically dependent on the match or mismatch between the occurrence of the larvae and availability of their zooplankton food (Cushing 1990) as well as other processes that affect early life-history stages (see Petitgas et al. 2013). Empirical data on exploited populations often show strong relationships between recruitment success, fisheries catches and climatic variables. These strong relationships have been demonstrated, for example, for cod (O’Brien et al. 2000; Brander and Mohn 2004; Cook and Heath 2005), plaice (Brunel and Boucher 2007), herring (Nash and Dickey-Collas 2005), mackerel (Jansen and Gislason 2011) and seabass (Pawson 1992). Correlations have been found between fish recruitment and various climate variables, including sea surface temperature, the NAO and even offshore winds (Table 12.2).

A number of publications describing the impact of climate variability (e.g. the NAO and AMO) on small pelagic fishes such as herring, anchovy or sardine in the North Sea have been published in recent years, for example those of Alheit et al. (2012) and Gröger et al. (2010). According to the most recent assessment of the UN Intergovernmental Panel on Climate Change (IPCC), the NAO is one of the climate indices for which it is most difficult to provide accurate future projections (IPCC 2013). Recent multi-model studies (e.g. Karpechko 2010) suggest overall that the NAO is likely to become slightly more positive (on average) in the future due to increased greenhouse gas emissions. Consequently, a slight tendency towards enhanced recruitment and larval abundance of these species in the future could be expected if the relationships observed in the past continue to hold.

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), but this relationship varies with regard to the different cod stocks that inhabit the North Atlantic (Planque and Frédou 1999). For stocks at the northern extremes (e.g. in the Barents Sea) or the western Atlantic (e.g. Labrador), warming leads to enhanced recruitment, while in the North Sea, close to the southern limits of the range, warmer conditions lead to weaker than average year classes (Drinkwater 2005). During the late 1960s and early 1970s, cold conditions were correlated with a sequence of positive recruitment years in North Sea cod

Table 12.2 Demonstrated correlations between recruitment success (year-class strength) and climatic variables for important fish and shellfish stocks in northwest Europe

Species	Source	Sea area	Correlation	Climate parameter
Plaice	van der Veer and Witte (1999) and Brunel and Boucher (2007)	Southern North Sea, English Channel	Negative	SST (Feb)
Herring	Nash and Dickey-Collas (2005)	North Sea	Negative	SST (winter)
Herring	Gröger et al. (2010)	North Sea	Positive	Winter NAO, AMO
Scallop	Shephard et al. (2010)	Isle of Man	Positive	SST (spring)
Cod	Brander and Mohn (2004)	North Sea, Irish Sea	Positive	Winter NAO
Cod	Planque and Frédou (1999) and O'Brien et al. (2000)	North Sea, West of Scotland, Irish Sea	Negative	SST (Feb–Jun)
Sandeel	Arnott and Ruxton (2002)	North Sea	Negative, Positive	Winter NAO, SST (spring)
Mackerel	Jansen and Gislason (2011)	North Sea	Unclear	SST (summer)
Brown shrimp	Siegel et al. (2005) and Henderson et al. (2006)	Bristol Channel, Wadden Sea	Positive, Negative	SST (Jan–Aug), Winter NAO
Sole	Henderson and Seaby (2005)	Bristol Channel	Positive	SST (spring)
Seabass	Pawson (1992)	English Channel	Positive	SST (summer)
Squid	Robin and Denis (1999)	English Channel	Positive	SST (winter)
Turbot	Riley et al. (1981)	Coastal UK	Positive	Offshore wind
Whiting	Cook and Heath (2005)	North Sea	Positive	SST
Saithe	Cook and Heath (2005)	North Sea	Positive	SST

SST Sea surface temperature; *NAO* North Atlantic Oscillation; *AMO* Atlantic Multi-decadal Oscillation

and subsequently high fisheries catches for a number of years thereafter (Heath and Brander 2001). In recent years however, despite several cold winters, cod have suffered very poor recruitment in the North Sea, although it is unclear whether this is a direct consequence of changed climatic conditions, reduced availability of planktonic prey items for larval fish or over-fishing of the parental stock (i.e. some sort of 'Allee effect') (Mieszkowska et al. 2009), or more intensive predation of cod larvae by pelagic fish stocks which have increased, such as herring and sprat (Engelhard et al. 2014a).

A clear seasonal shift to earlier appearance of fish larvae has been described for several species at Helgoland Roads in the southern North Sea (Greve et al. 2005), and this has been linked to marked changes in zooplankton composition and sea surface temperature in this region (Beaugrand et al. 2002). In particular, there has been a decline in the abundance of the copepod *Calanus finmarchicus* but an increase in the closely related but smaller species *C. helgolandicus*. *Calanus finmarchicus* is a key 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 (Reid et al. 2001, 2003; Beaugrand et al. 2003). *Calanus helgolandicus* occur at the wrong time of the year to be of use to emerging cod larvae. Greve et al. (2005) suggested that in ten cases both the 'start of season' and 'end of season' (Julian date on which 15 and 85 % of all larvae were recorded respectively), were correlated with sea surface temperature. Strongly significant relationships were observed for plaice, sole and horse mackerel as well as for many non-commercial species including scaldfish, and Norway bullhead *Taurulus lilljeborgi*.

Fincham et al. (2013) examined the date of peak spawning for seven sole stocks based on market sampling data in England and the Netherlands. Four out of seven stocks were shown to have exhibited a significant long-term trend towards earlier spawning (including the east-central North Sea, southern North Sea, and eastern English Channel) at a rate of 1.5 weeks per decade since 1970. Sea surface temperature during winter affected the date of peak spawning, although the effect differed between stocks. Recruitment is critically dependent on the match or mismatch between the occurrence of the larvae and the availability of their food (Cushing 1990) and other climate-sensitive processes (Peck and Hufnagl 2012; Llopiz et al. 2014), thus a change in spawning date could have knock-on effects for larval survival and hence future fisheries.

It is important to note that extensive fishing can cause fish populations to become more vulnerable to short-term natural climate variability (e.g. Ottersen et al. 2006) 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 and Blanchard 2004). Cook and Heath (2005) examined the relationship between sea surface temperature and recruitment in a number of North Sea fish species (cod, haddock, whiting, saithe, plaice, sole) and concluded that if the recent warming period were to continue, as suggested by climate models, stocks which express a negative relationship with temperature (including cod) might be expected to support much smaller fisheries in the future. In the case of cod, climate change has been estimated to have been eroding the maximum sustainable yield at a rate of 32,000 tonnes per decade since 1980. 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, and that current 'precautionary reference' limits or targets (such as F_{MSY}), calculated by International Council for the Exploration of the Sea (ICES) on the basis of historic time series, may be unrealistically optimistic in the future.

For Atlantic mackerel, increases in sea surface temperature are known to affect growth, recruitment and migration with subsequent impacts on permissible levels of exploitation (Jansen and Gislason 2011). Jansen et al. (2012) used information on larval fish from the Continuous Plankton Recorder (CPR) to show that abundance has declined dramatically in the North Sea since the 1970s and also that the spatial distribution of mackerel larvae seems to have changed. Whether these trends can be ascribed to changes in climatic conditions remains unclear, although development and/or mortality of mackerel eggs is known to be very sensitive to seawater temperature (Mendiola et al. 2007).

There have been many attempts to include climatic variables in single-species population models (e.g. Hollowed et al. 2009), and thereby to project how the productivity of fish stocks will be affected 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 within the 'stock-recruit' relationship in order to make medium or long-term forecasts. Clarke et al. (2003) used projections of future North Sea temperatures and estimated the likely impact of climate change on the reproductive capacity of cod, assuming that the high level of mortality inflicted by the fishing industry (in 2003) continued into the future. Outputs 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 needed for the cod stock to recover was not greatly affected by the particular climate scenario chosen (and was generally around five to six years), although overall productivity was affected and spawning stock biomass (SSB) once 'recovered' was projected to be considerably less than would have been the case assuming no temperature increase (251,035 tonnes compared to 286,689 tonnes in 2015).

12.3.1.3 Ocean Acidification and Low Oxygen

Carbon dioxide (CO_2) concentrations in the atmosphere are rising as a result of human activities and are projected to increase further by the end of the century, as carbon-rich fossil fuels such as coal and oil continue to be burned (Caldeira and Wickett 2003). Uptake of CO_2 from the air is the primary driver of ocean acidification. Modelling and observational studies suggest that the absorption of CO_2 by seawater has already decreased pH levels in the global ocean by 0.1 pH units since 1750 (Orr et al. 2005), which equates to an average increase in surface ocean water acidity worldwide of about 30 % since pre-industrial times, and that the present rate of change is faster than at any time during the previous 55 million years (Pearson and Palmer 2000).

Modelled estimates of future seawater pH in the North Sea are generally consistent with global projections. However, variability and uncertainties are considerable due to riverine inputs, biologically-driven processes and geochemical interactions between the water column and sea-bottom sediments (Blackford and Gilbert 2007; Artioli et al. 2012). Under a high CO_2 emission scenario, model outputs indicate that much of the North Sea seafloor is likely to become undersaturated with regard to aragonite (a form of calcium carbonate used by some marine organisms to build their shells or skeletons) during late winter/early spring by 2100 (Artioli et al. 2012). Ocean acidification may have direct and indirect impacts on the recruitment, growth and survival of exploited species (Fabry et al. 2008; Llopiz et al. 2014) and some species may become more vulnerable to ocean acidification with increases in temperature (Hale et al. 2011). Impacts may be particularly apparent for animals with calcium carbonate shells and skeletons such as molluscs, some crustaceans, and echinoderms (Hendriks et al. 2010; Kroeker et al. 2010), but studies show large variations in responses to ocean acidification between and within taxonomic groups. Several major programmes of research are underway in Europe to determine the possible consequences of future ocean acidification. In laboratory studies, significant effects have been noted for several important commercial shellfish species, notably mussels, oysters, lobster and *Nephrops* (Gazeau et al. 2010; Agnalt et al. 2013; Styf et al. 2013).

A preliminary assessment in 2012 estimated the potential economic losses to the UK shellfish industry under ocean acidification (Pinnegar et al. 2012). Four of the ten most valuable marine fishery species in the UK are calcifying shellfish and the analyses suggested losses in the mollusc fishery (scallops, mussels, cockles, whelks etc.) could amount to GBP 55–379 million per year by 2080 depending on the CO_2 emission scenario. Thus, there is a clear economic reason to improve understanding of physiological and behavioural responses to ocean acidification, and a Europe-wide assessment of economic consequences is currently underway within the German BIOACID programme.

Fin-fish species are thought to be most vulnerable to ocean acidification during their earliest life stages, although experiments on North Sea species (such as cod and herring) have so far shown that they are relatively robust (e.g. Franke and Clemmesen 2011). Indirect food-web effects may be more important for fin-fish, than direct physiological impacts (Le Quesne and Pinnegar 2012). To date, few studies have attempted to investigate the potential bottom-up impacts of ocean acidification on marine food webs, and hence on fisheries (although see Kaplan et al. 2010; Ainsworth et al. 2011; Griffith et al. 2011). In their economic analysis, Cooley and Doney (2009) did account for "fish that prey directly on calcifiers". These authors suggested that indirect economic consequences of ocean acidification could be substantial. Clearly, more work is needed before definitive conclusions can be drawn about the socio-economic implications of ocean acidification for the fishing industry and society as a whole.

Reduced oxygen concentrations in marine waters have been cited as a major cause for concern globally (Diaz and Rosenberg 2008), and there is evidence (Queste et al. 2012) that areas of low oxygen saturation have started to proliferate in the North Sea. Whether these changes are a result of long-term climate change remains unclear and it is also unclear whether such changes will impact on commercial fish species and their fisheries. Unlike parts of the Baltic Sea, which regularly experience complete anoxia (lack of oxygen), regions of the North Sea only experience reduced oxygen conditions (65–70 % saturation, 180–200 μMol dm^{-3}). Therefore it is uncertain whether North Sea fish stocks will suffer major mortality of eggs and larvae due to changes in oxygen levels (as is the case in the Baltic Sea), and it is perhaps more likely that they will experience more subtle, non-lethal, effects in the future. Several authors have highlighted how oxygen concentrations, low pH and elevated temperature interact and determine 'scope for growth' (e.g. Pörtner and Knust 2007). These findings have been used as the basis for models predicting size and distribution in North East Atlantic fishes (Cheung et al. 2013). Laboratory studies concerning low oxygen conditions have been used to predict fish distribution and habitat suitability (Cucco et al. 2012). Some types of organism are more affected than others. Larger fish and spawning individuals can be more affected by low oxygen levels owing to their higher metabolic rates (Pörtner and Farrell 2008). There are certain thresholds below which oxygen levels affect the aerobic performance of marine organisms (Pörtner 2010), although this is very dependent on the species or type of organism, respiration mode, and metabolic and physiological requirements, with highly active species being less tolerant of low oxygen conditions (Stramma et al. 2011). *Nephrops norvegicus* juveniles show sub-lethal effects at oxygen concentrations below 156 μMol dm^{-3}, but adults are more robust, although their ability to tolerate other environmental stresses (for example elevated temperature) is severely compromised (Baden et al. 1990). There are few projections of future oxygen concentrations in the North Sea, although modelling was undertaken for three locations by van der Molen et al. (2013). These authors were able to provide some insight into future conditions, assuming a SRES A1B scenario to 2100. In particular, the model suggested marked declines in oxygen concentration at all sites as a result of simulated changes in the balance between phytoplankton production and consumption, changes in vertical mixing (stratification) and change in oxygen solubility with temperature. A parallel study by Meire et al. (2013) for the 'Oyster Grounds' site (also using the SRES A1B scenario) suggested that bottom water oxygen concentrations in late summer could decrease by 24 μM or 11.5 % by 2100.

12.3.2 Pathogens, Pests and Predators

A key issue for North Sea fish and shellfish is the link between climate change and the prevalence of pathogens or harmful algal bloom (HAB) species. A global review suggested that marine pathogens are increasing in occurrence, and that this increase is linked to rising seawater temperature (Harvell et al. 1999) with possible consequences for commercial fisheries and aquaculture.

The presence of certain pathogens or algal toxins in seawater samples or in tissues harvested from shellfish can result in temporary closure of a fishery. Many pathogens that occur in European shellfish are very sensitive to seawater temperature and salinity, for example the bacteria *Vibrio parahaemolyticus* and *V. vulnificus* that pose a significant threat to human health (Baker-Austin et al. 2013). *Vibrio* species proliferate rapidly at temperatures above 18 °C and incidents of shellfish-associated gastrointestinal illness in Europe have been noted during heat waves (Baker-Austin et al. 2013). In the United States, *Vibrio*-related incidents cost the economy more than any other seafood-acquired pathogen and these incurred costs have increased dramatically in recent years (Ralston et al. 2011). In contrast, *Norovirus*, another major cause of shellfish-acquired gastroenteritis, occurs most frequently in winter and following periods of high precipitation and hence is associated with flash-flooding and runoff from sewers (Campos and Lees 2014). Future projections of precipitation (rain and snowfall) and river run-off for catchments surrounding the North Sea suggest that intense rainfall and hence extreme river flows will occur more often in the future, particularly during winter, and so considerable changes could be anticipated in the epidemiology and proliferation of marine pathogens—and therefore exposure risk for European citizens consuming seafood (Pinnegar et al. 2012).

Reports of increased abundance of jellyfish in the media and in scientific literature over recent decades have raised concerns over the potential role of climate change in influencing outbreaks (Atrill et al. 2007; Purcell 2012) and in possible implications for commercial fisheries and aquaculture. Data obtained from the CPR survey show an increasing occurrence of jellyfish in the central North Sea since 1958 that this may be positively related to the NAO and Atlantic inflow (Lynam et al. 2004; Atrill et al. 2007). High jellyfish numbers are potentially detrimental to fisheries both as competitors with, and predators of, larval fish (Purcell and Arai 2001). In particular, negative impacts of jellyfish on herring larvae have been noted (Lynam et al. 2005) and this is now a major focus of scientific attention.

Climate change can also influence the presence of potential predators. For example Kempf et al. (2014) demonstrated that grey gurnard *Eutriglia gurnardus*, has expanded its high density areas in the central North Sea northward over the last two decades to overlap with that of 0-group cod. Grey gurnard are thought to be important predators of juvenile cod, hence recruitment success of cod was found to be negatively correlated with the degree of spatial overlap between the two species. Similar fears have been voiced by fishers regarding the recent expansion of hake in the northern North Sea (see Sect. 12.3.1.1), since hake is also known to be a voracious predator of smaller fish.

12.3.3 Fishery Operations

Through its effects on seawater temperature as well as its influence on storm conditions climate change can affect the performance of fishing vessels or gears, as well as vessel safety and stability at sea.

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

In tropical tuna (the main target of Europe’s distant-water fleet), strong El Niño events along the west coast of the Americas typically result in a deeper thermocline, and declines in yellowfin tuna *Thunnus albacares* catches (see Miller 2007) because fish are able to spread out in the water column beyond the reach of commercial fisheries. Poor catch rates during the intense 1982–1983 El Niño played a role in the migration of the entire US tuna fleet from the Eastern Pacific to the Western and Central Pacific. Similar processes and mechanisms, but on a smaller spatial scale, appear to influence catch rates in North Sea pelagic fisheries, such as those targeting herring. Maravelias (1997) demonstrated that temperature and depth of the thermocline, appear to be key factors that modulate both the presence and relative abundance of herring within the northern North Sea. Herring appeared to avoid the cold bottom waters of the North Sea during the summer, probably due to the relatively poor food resources there. This greatly affected ‘catchability’.

At present, confidence in the wind and storm projections from global climate models (GCMs) and downscaled regional climate models (RCMs) is relatively low, with some models suggesting that northwest Europe might experience fewer storms and others suggesting an increase (Woolf and Wolf 2013). In general, models suggest that climate change could result in a north-eastward shift of storm frequency in the North Atlantic, although the change in storm intensity or frequency that this implies is not clear (Meehl et al. 2000; Ulbrich et al. 2008). The winter of 2013/14 was the stormiest in the last 66 years with regard to the southern North Sea and the wider British Isles (Matthews et al. 2014) and this is known to have coincided with major disruption to the fishing industry throughout the region. Months of high winds and high seas left many fishers unable to work, and caused millions of Euros worth of damage—as well as a lack of fish and higher prices on fish markets.

12.3.3.1 Climatic Influences on ‘Catchability’

There is little evidence of significant changes in catchability of demersal trawl gears in the North Sea as a result of climate change or poor weather conditions, although Walden and Schubert (1965) examined wind and catch data, and found that wind direction and force were correlated with catch at a few locations. Similarly Harden Jones and Scholes (1980) investigated the relations between wind and the catch of a Lowestoft trawler. Their analysis showed that over the course of a year, catches of plaice were lowest with northerly winds but that the reverse was true for cod. Long-term projections for winds over the North Sea are highly uncertain, but several authors (notably Wang et al. 2011) have suggested a climate-change-related upward trend in storminess in recent years. Analyses (de Winter et al. 2013) under a range of different climate change scenarios, do not anticipate changes in annual maximum wind speed over the next 50–100 years, however they do suggest that annual extreme wind events will occur more often from western directions. This is particularly relevant for fishing boats in the German

Bight, as such a shift would imply larger extreme waves and surge levels in this region.

Poulard and Trenkel (2007) reported that the impact of wind strength on catchability depends on the habitat preferred by a given species. For a bottom trawl survey in the Bay of Biscay, catches of benthic and demersal species were significantly affected by wind condition whereas no effect was detected for pelagic species. Similarly, Wieland et al. (2011) examined bias in estimates of abundance and distribution of North Sea cod during periods of strong winds. Wind speed had significant effects on catch rates, and specifically catches were reduced during the strongest winds. Strong winds prevailing over a prolonged period lead to poor visibility in shallow coastal waters, caused mainly by resuspension of bottom sediments. North Sea trawlers and especially 'flyshooters' would usually not fish in that area under such conditions due to the expectation of poor catches whereas gillnets may perform well in this case.

Fish are known to behave differently in turbid versus clearer waters. For example, Meager and Batty (2007) examined activity of juvenile cod and found both longer prey-search times and higher activity in turbid conditions, and suggested that such behaviour might increase energetic costs and also make the cod more vulnerable to fishing gears and potential predators. Capuzzo et al. (2015) demonstrated that the southern North Sea has become significantly more turbid over the latter half of the 20th century, and that this may be related to changes in seabed communities, weather patterns, and increased coastal erosion. Gill net catches are typically higher in turbid waters after storms. Ehrich and Stransky (1999) found that catch rates of some groundfish species in the North Sea exhibited significant variability following strong and severe gales (periods of strong winds from 50 to 102 km h^{-1}). Catches of dab, solenette, plaice and sole all changed markedly between the first and second day after the storm.

12.3.3.2 Vessel Stability and Performance

An increase in the frequency or severity of storms could have negative consequences for the ability of fishing boats to access resources in the future or could have consequences for vessel stability and performance. Abernethy et al. (2010) reported that 85 % of fishers interviewed as part of a survey in southern England, elected to stay in port during bad weather due to the risk of gear loss and increased fuel consumption. Fishing remains a dangerous occupation. A research project, published in 2007 showed that the fatal accident rate for UK fishers for the decade 1996–2005 was 115 times higher than that of the general workforce (MAIB 2008). In the United States, severe weather conditions contributed to 61 % of the 148 fatal fishing vessel disasters reported between 2000 and 2009 (Lincoln and Lucas 2010). In Denmark, more than half of fatalities reported were caused by foundering/capsizing due to stability changes in rough weather (Laursen et al. 2008). In the UK, the majority of vessel losses recorded (52 %) were due to flooding/foundering, and most involved small vessels of less than 12 m in length (MAIB 2008). Most flooding/foundering losses occurred in moderate weather. However, this needs to be considered against the likelihood that there would be fewer fishing vessels at sea during extreme weather conditions (MAIB 2008).

Dramatic increases in wave height occurred in the North Sea between 1960 and 1990, but these are now viewed as one feature within a longer history of variability (Woolf and Wolf 2013). Future patterns of storminess are poorly understood, with little consensus between models and highly uncertain model outputs. Changes in storminess and associated consequences for fishing operations is an under-researched topic, with no recent assessments of vessel operating envelopes or the willingness of vessel owners/skippers to put to sea. Laevastu and Hayes (1981) suggested that modern high-sea fishing vessels usually have to stop fishing at wind speeds of 50–78 km h^{-1} (Force 7 to 8 on the Beaufort scale), whereas coastal fishing vessels in the North Sea find difficulty in operating at wind speeds of 39–49 km h^{-1} (Force 6 on the Beaufort scale). A number of modelling approaches have been applied in the North Sea to try to predict the behaviour of fishers and the distribution of fishing vessels (e.g. Hutton et al. 2004) but none have yet included storms or weather disruption in their analyses.

12.3.3.3 Assessing Economic Implications

There has been little research directed towards understanding the future implications of climate change for fishing fleets, fishers, coastal economies and society directly. This is certainly the case with regard to countries surrounding the North Sea. However, a number of studies have set out to investigate the vulnerability and adaptive capacity of the fisheries sector at a global scale (McClanahan et al. 2008; Allison et al. 2009). Vulnerability to climate change depends upon three key elements: exposure to physical effects of climate change; sensitivity of the natural resource system or dependence of the national economy upon economic returns from the fishing sector; and the extent to which adaptive capacity enables these potential impacts to be offset. Allison et al. (2009) ranked North Sea countries very low in terms of overall vulnerability, largely due to low rates of fish consumption in the surrounding countries, highly diversified economies and only moderate exposure to future climate change. Similarly, Barange et al. (2014) categorised all North Sea countries as either low (Norway) or very low in terms of nutritional and economic dependence on fisheries. However fisheries represent an important component of employment in certain North Sea regions (EU 2011), notably in Shetland where 22 % of all jobs are estimated to be in fisheries/fisheries-related industries, and Urk in the Netherlands where 35 % of jobs rely on fisheries.

Cheung et al. (2010) estimated future changes in maximum potential catch (a proxy for maximum sustainable yield) given projected shifts in the distribution of exploited species and changes in marine primary productivity. This study suggested that climate change may lead to large-scale redistribution of global maximum catch potential, with an average of 30–70 % increase in yield of high-latitude regions (north of 50°N in the northern hemisphere), but a drop of up to 40 % in the tropics. North Sea countries are anticipated to gain very slightly in maximum potential catch but not as much as Nordic countries such as Norway and Iceland. This region will witness increases in catches of some commercial species but decreases in others, and thus the gains and losses are expected to broadly balance out.

Working at a national level, Jones et al. (2015) used a similar bioclimate envelope model (see Fig. 12.4) to investigate economic implications for fisheries catch potential in the UK exclusive economic zone (EEZ) specifically. Maximum catch potential was calculated for each species in both the reference and projection periods using an algorithm that takes into account net primary production and range area. Results suggested that the total maximum catch potential will decrease within the UK EEZ by 2050, although this was heavily influenced by an assumed decline in plankton productivity. Extending these projections into a cost benefit analysis resulted in a median decrease in net present value of 10 % by 2050. Net present value over the study period further decreased when trends in fuel price were extrapolated into the future, becoming negative when capacity-enhancing subsidies were removed. This study highlights key factors influencing future profitability of fisheries and the importance of enhancing adaptive capacity in fisheries and resilience to climate change.

Uncertainty is inherent in fisheries management, so there is an expectation of change and a wealth of knowledge and experience of coping with and adapting to this uncertainty. Badjeck et al. (2010) argued that diversification is a primary means by which individuals can reduce risk and cope with future uncertainty. A recent study commissioned by the UK Department for Environment, Food and Rural Affairs included a detailed assessment of whether the fish catching sector might be expected to adapt to the opportunities and threats associated with future climate change over the next 30 years (Defra 2013). This assessment built heavily on the species projections of Jones et al. (2012, 2013—see Sect. 12.3.1.1) and looked for examples of current adaptation by the sector, focusing on species increasing in the UK EEZ (such as anchovy, squid, seabass) and also on past increases in scallops, boarfish *Capros aper*, and hake. The key adaptation actions identified included:

- Travelling further to fish for current species, if stocks move away from existing ports.
- Diversifying the livelihoods of port communities, this may include recreational fishing where popular angling species become locally more abundant (e.g. seabass).
- Increasing vessel capacity if stocks of currently fished species increase.
- Changing gear to fish for different species, if new or more profitable opportunities to fish different species are available.
- Developing routes to export markets to match the changes in catch supplied. These routes may be to locations (such as southern Europe) which currently eat the fish stocks which may move into northern waters.
- Stimulating domestic demand for a broader range of species, through joined-up retailer and media campaigns.

Many of the same adaptation options were also highlighted by McIlgorm et al. (2010) who reviewed how fishery governance may need to change in the light of future climate change, also the ACACIA report (ACACIA 2000) prepared as part of the European impact assessment for the IPCC Third Assessment which included a short chapter on fisheries. Vanderperren et al. (2009) provided a brief overview for Belgian marine fisheries. These authors noted the strong specialisation of the Belgian fleet with regard to a single fishing method (93 % beam trawlers) and target species (mainly flatfish) and that this makes the sector particularly vulnerable to changing circumstances. Possible adaptation measures as well as technological and economic consequences for the fleet were detailed (see Van den Eynde et al. 2011), and the elaboration of scenarios for secondary impacts at different points in time (2040, 2100) is ongoing.

Sumaila and Cheung (2009) attempted to estimate the necessary annual costs of adaptation to climate change in the fisheries sector worldwide. Adaptation to climate change is likely to involve an extension of existing policies to conserve fish stocks and to help communities. In Europe the estimated annual cost of adaptation was USD 0.03–0.15 billion, a small fraction of the costs (USD 1.05–1.70 billion) anticipated for East Asia and the Pacific.

12.4 International Fish Markets and Commodity Chains

Fisheries in the North Sea should not be viewed in isolation given that seafoods are traded globally and many North Sea countries are both exporters and importers of fish and shellfish commodities. It could be expected that prices of a particular commodity would reflect local patterns of availability (supply) and hence that the price of fish might even reflect regional climatic conditions (see Pinnegar et al. 2006). However this is rarely the case, given that supplies can often be secured from elsewhere and thus prices may remain low, even if locally resources become scarce. Cod stock status in the North Sea currently remains very low, possibly as a result of long-term climatic influences on recruitment, but catches are at an all-time high further north in the Barents Sea (ICES 2014b) and thus cod prices in Europe are supressed. A clear adaptation response in the face of ensuing climate change is to obtain fish from sources further north (either by trade or by shifting the location of fishing fleets where this is possible). As other countries around the word also need to secure sufficient food for growing populations, and have considerably higher buying-power (notably China, which in 2030 will account for 38 % of total fish consumption), European countries may find the ability to secure sufficient fish products from Nordic (non-EU) countries, such as Norway, Iceland and Greenland, much more difficult in the future (World Bank 2013).

Another international fisheries topic that has received considerable attention in recent years has been the link between global climate and fishmeal supplies and markets (e.g. Merino et al. 2010a, b). Aquaculture and animal feed production depend on fishmeal and fish oil as their primary source of protein, lipids, minerals and essential Omega 3/6 fatty acids. Every year 30 million tonnes of anchovita *Engraulis ringens, E. mordax* etc., sardines *Sardinops sagax, Sardina pilchardus* and other small pelagic fish are reduced into 6 million tonnes of fishmeal. More than half of this is derived from Peruvian/Chilean anchoveta although Denmark and Norway supply an additional 12 % based on North Sea sandeel, sprat, Norway pout and blue whiting as well as Arctic capelin *Mallotus villosus*. A lack of supply in Peruvian anchoveta (for example during El Niño climatic regimes) raises the price of fishmeal from elsewhere (e.g. the North Sea) and can influence the behaviour of European fishers, with indirect (e.g. predator-prey) consequence for other fish stocks.

12.5 Conclusions

North Sea fisheries may be impacted by climate change in various ways and consequences of rapid temperature rise are already being felt in terms of shifts in species distribution and variability in stock recruitment. While an expanding body of research now exists on this topic, there are still many knowledge gaps, especially with regard to understanding how fishing fleets themselves might be impacted by underlying biological changes and what this might mean for regional economies. Historically, fisheries managers and fishers have had to adapt to the vagaries of weather and climate, however the challenge presented by future climate change should not be underestimated and it is clear that fish communities and the fisheries that target them will almost certainly be very different in 50 or 100 years and that management and governance will need to adapt accordingly.

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