MARINE CLIMATE CHANGE IMPACTS PARTNERSHIP: SCIENCE REVIEW
MCCIP Science Review 2017: XXX
Published online subject to final type-setting & images
doi: 10.14465/2017.arc10.007-fis

Fisheries

John K. Pinnegar[a,b], Angus Garrett[c], Stephen D. Simpson[d], George H. Engelhard[a,b], and Jeroen van der Kooij[a]

[a] *Centre for Environment, Fisheries and Aquaculture Science, Lowestoft, NR33 0HT, UK*
[b] *School of Environmental Sciences, University of East Anglia, Norwich, NR4 7TJ, UK*
[c] *Seafish, 18 Logie Mill, Logie Green Road, Edinburgh, EH7 4HS, UK*
[d] *Biosciences, College of Life & Environmental Sciences, University of Exeter, Stocker Road, Exeter, EX4 4QD, UK*

KEY HEADLINES

- Since 2006, the evidence base with regard to understanding climate change impacts on the UK fishing industry has advanced substantially, although many of the key themes covered in 2006 remain highly relevant today (e.g. recruitment variability, shifts in distribution, newly emerging fisheries).
- A particular focus in recent years has been the spread of mackerel into Icelandic and Faroese waters, with consequences for fisheries quota allocation and governance. Changes in mackerel distribution have been linked to several possible factors, including warmer seas, changes in food availability and a density-dependent expansion of the stock. The different mechanisms are not necessarily mutually exclusive and may have acted synergistically.
- In the North Sea, where an important summer trawl fishery targeting squid has developed, squid numbers have increased dramatically over the past 35-years. Significant positive relationships were found between this increase in squid abundance and climate variables such as sea surface temperature.
- Over the past few years, many hundreds of papers have been published focusing on the impacts of ocean acidification, however, there is still a lack of conclusive evidence as to possible consequences for commercial fisheries. A recent economics study for Europe as a whole suggests annual economic losses by 2100 in the United Kingdom, the Channel Islands and the Isle of Man could amount to 97.1, 1.0 and 12.7 million US$, respectively, under a worst-case scenario.
- The winter of 2013/14 was identified as one of the stormiest (in terms of wind speeds, wave heights, etc.) of the past 66 years. The UK fishing industry was severely disrupted, with many vessels tied up in port for at least five months. Understanding of how storminess in the UK will be impacted by future climate change remains very limited.
- European seabass had been held up as a 'poster child' of marine climate change in the UK. Evidence suggests that populations did expand dramatically in the early 2000s, however in recent years fishing mortality has reached unsustainable levels and advance of this species has been severely curtailed.
- Changes in fish distribution patterns have featured in all previous MCCIP report cards. Many additional UK studies have been conducted over the past 10 years, using scientific survey data and information from commercial catch-per-unit-effort, that have confirmed the initial findings.
- For many years it has been argued that cod might not be able to persist around the UK in the future, if seawater temperatures continue to rise. Despite dramatic and deliberate reductions in fishing mortality, cod stocks have not 'recovered as quickly as expected, largely as a result of continued poor recruitment related to prevailing climatic conditions. Events of the past 10 years have followed trajectories predicted by modelling studies.

1. INTRODUCTION

Fishing remains one of the most important maritime activities in the the United Kingdom. In 2014, the most recent year for which published data were available (MMO, 2015), UK fishing vessels landed 756,000 tonnes of fish and shellfish, accruing a revenue of around £861 million. This compares to 610,000 tonnes and £610 million in 2006; the year in which the first MCCIP report card was published. Fishing now (in 2014) employs around 11,845 fishermen, compared to 12,934 in 2006 and there has been a similar decrease in the number of UK fishing vessels over this period – declining from 6,752 in 2006 to 6,382 in 2014 (the total engine power of the fleet has declined from 863,496 kW to 789,714 kW). The recent contraction in the UK fishing industry has been a result of deliberate interventions to control fishing pressure and to ensure sustainable exploitation of European fish stocks, but also, to some extent, reflects the underlying influence of climatic factors that determine the level of fishing that can be sustained by fish populations, given the prevailing environmental conditions.

In terms of tonnage the most important species to UK fisheries (landings in the UK and abroad) in 2014 were mackerel *Scomber scombrus* (288,000 t), herring *Clupea harengus* (97,700 t), scallops *Pecten maximus* and *Aequipecten opercularis* (39,100 t) and haddock *Melanogrammus aeglefinus* (36,100 t). In terms of value, they were mackerel (£227 million), *Nephrops norvegicus* [langoustine/scampi] (£99 million), scallops (£59 million) and haddock (£50 million). Over the past 10 years, since the first MCCIP report card, the composition of UK catches has changed appreciably, for example mackerel have become more important in terms of overall tonnage, with increases also observed for crabs (mostly *Cancer pagurus*), whelks *Buccinum undatum*, plaice *Pleuronectes platessa* and cod *Gadus morhua*. Meanwhile catches of *Nephrops* and blue whiting *Micromesistius poutassou* have decreased over the past 10 years.

Per capita consumption of fish in the UK has remained relatively stable (and low) at around 7.6 kg/person/yr (compared to 8.7 kg/person/yr in 2006) and imports have stayed broadly similar at 721,000 tonnes (753,000 tonnes in 2006) including 91% of all cod (92.5% in 2006), and 53% of all haddock (66% in 2006). The vast majority of the fish consumed by UK citizens (supermarkets refer to "the big 5": cod, haddock, tuna, salmon and prawns; which account for 80% of the British retailer's total seafood sales) are derived from imports, whereas the majority of fish and shellfish actually caught by UK fishermen are exported.

Since 2006 the evidence base with regard to understanding climate change impacts on the UK fishing industry has advanced substantially, although many of the key themes covered in the 2006 MCCIP report (Pinnegar, 2006) remain highly relevant today (e.g. recruitment variability, shifts in distribution, newly emerging fisheries). A considerable amount of new modelling and observational work has been carried out over this intervening period (e.g. Rijnsdorp *et al.*, 2009; Cheung *et al.*, 2011; Petitgas *et al.,* 2013; Jones *et al.*, 2015; Rutterford *et al.*, 2015) offering new insights into likely future consequences for fish populations or distributions and hence for UK fisheries. Added to this MCCIP published a special report card in 2012 focusing on fish, fisheries and aquaculture explicitly, and this spurred considerable media interest in this topic, with articles published in Scientific American, The Guardian, BBC Wildlife and The Scotsman, as well as television and radio interviews. Various campaigns and activities in the UK as well as publication of the 5th Assessment Report of the IPCC in 2014 seem to have also coincided with acceleration in the number of relevant peer-reviewed scientific publications. In earlier years the emphasis was mostly on the biology of commercially important species, whereas in recent years, greater emphasis has been placed on understanding economic and social consequences, especially for fleets and fishermen (e.g. Fernandes *et al.,* 2017; Jones *et al.,* 2015).

Notably, introduction of reporting requirements under the 2008 UK Climate Change Act seems to have prompted new work related to sea fisheries. In 2012 Defra commissioned its 'Economics of Climate Resilience' (ECR) report on 'sea fisheries' and this study included a detailed assessment of whether or not the UK fish catching sector could be expected to adapt to the opportunities and threats associated with future climate change. In December 2015, Seafish (the trade body for the commercial fisheries sector in the UK) published a report "Understanding and responding to climate change in the UK wild capture seafood industry" (Garrett *et al.*, 2015) that aimed to support the UK seafood industry in developing a managed adaptive approach to climate change.

At the European level, initiatives such as the North Sea Region Climate Change Assessment (NOSCCA) have attempted to provide a broader perspective and have included chapters on fisheries, drawing heavily on the outputs from MCCIP. Similarly, in 2016 two EU Horizon 2020 research projects (CERES and CLIMEFISH) were commissioned, with the aim to "provide the knowledge, tools and technologies needed to successfully adapt European fisheries and aquaculture sectors in marine and inland waters to anticipated climate change". This will include economic assessments of climate change impacts on these two sectors, but also the development of practical adaptation measures that fishermen, farm owners and aquatic resource managers can adopt to successfully adapt to forthcoming climate change threats or to capitalise on emerging opportunities.

The following briefing paper aims to summarize what has happened since the last MCCIP report card was published in 2013, but also to take a longer-term retrospective view of how the field has moved on over the past 10 years, since the first MCCIP report was published in 2006.

2. TOPIC UPDATE

2.1 Distributional Shifts

One of the themes that has repeatedly been raised in MCCIP reports over the past 10 years has been observed shifts in the distribution of species, including commercial fish. A particular focus has been the apparent westward and northwest-ward spread of Atlantic mackerel into Icelandic and Faroese waters, with consequences for fisheries quota allocation and governance. Since 2013 the scientific evidence-base with regard to Atlantic mackerel, Scotland's most valuable fishery, has increased considerably, and hence we are now better able to describe the drivers behind this recent phenomenon, and consequences for fisheries in more detail.

After spawning, which typically takes place off northwest Scotland (but to some extent along the entire European shelf from Gibraltar to Scotland) from February to July, mackerel migrate to the feeding grounds. Until the mid-2000s, the feeding grounds were mostly limited to the northern part of the North Sea and the Norwegian Sea, although there are indications of previous expansions into Icelandic waters during warm periods in the past, such as in the 1920s to mid-1960s (Astthorsson *et al.*, 2012). In Icelandic waters, mackerel were previously only sporadically observed and hence they were considered to be vagrants (Astthorsson et al., 2012). In 2006, mackerel was first observed in significant amounts east of Iceland as by-catch in the Norwegian spring-spawning herring fishery (they have since been observed as far north as Svalbard; Berge *et al.*, 2015) and a large directed mackerel fishery has grown to exploit the expanding population. The recent changes in mackerel distribution have been linked to several possible factors, including warmer seas, changes in food availability and a density-dependent expansion of the stock (ICES, 2013a). The increase of mackerel also in its traditional feeding area of the northern North Sea (van der Kooij *et al.*, 2016) has led to increasing pressure on local food resources and, possibly compounded by small numbers of zooplankton prey in some parts of its traditional habitat (Norwegian Sea, ICES 2013b), is likely to have driven this expansion through a density-dependent mechanism. This is also confirmed by a decreasing length and weight-at-age in recent years (Olafsdottir *et al.*, 2016). As temperatures have increased in the north and northwestern extremities of the species' distribution, where colder water temperatures were previously a limiting factor (ICES, 2013a), mackerel have been able to expand their range. The different mechanisms may, therefore, have acted synergistically (Hughes *et al.*, 2015).

Hughes et al., (2014) suggested that sea surface temperature (SST) 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 SST for the region). However, the association with climatic indices is not straightforward (Hughes *et al.*, 2015). A comprehensive study of mackerel records by Astthorsson *et al.*, (2012) highlighted 2007 as the year when distribution first started to change, but found that there were warmer years before 2007, so a simple temperature mechanism does not seem likely. This observation is supported by the lack of a strong linear relationship between mackerel occurrence off Iceland and the Atlantic Multidecadal Oscillation (AMO) — a commonly used proxy for variations in North Atlantic seawater temperature. However, Hughes *et al.*, (2015) detected a significant climate effect on the depth of area fished, where mackerel were generally caught in areas of greater depth during positive AMO years. In addition, the AMO appeared to have a non-linear relationship with the spatial extent of mackerel catches, with an increased total fishing area in positive AMO years.

The relationship of the depth of area fished with the winter North Atlantic Oscillation (NAO) was more complex. Most positive winter NAO years were associated with fishing in deeper areas, but with some suggestion of fishing in shallower regions in the most positive NAO years (Hughes *et al.*, 2015). Similarly, negative NAO values were associated with fishing in shallower areas on average, except for the two most negative NAO years, where fishing was in deeper areas. The non-linear relationships between catch variables and climate indices may reflect the complexity of the oceanographic processes linked to an index such as the NAO. For example, a positive NAO leads to warm temperature anomalies in the North and Norwegian Seas, but a negative winter NAO is associated with warm temperatures west of Iceland (Hughes *et al.*, 2015).

In October 2009, North Sea mackerel appeared to have moved away from the Norwegian Sector and Norwegian vessels attempted to follow the fish westwards resulting in disagreements over permissible catches by Norwegian boats in Scottish (EU) waters (see Fishing News, 9th October 2009). Shortly after, Iceland and the Faroe Islands unilaterally claimed quota for mackerel (146,000 and 150,000 tonnes, respectively, in 2011; or 46% of total catches), since the species had suddenly attained high abundance in their territorial waters for the first time. These events prompted difficult political negotiations that lasted for a further five years. A partial resolution to the long-standing political dispute regarding mackerel quotas in the North East Atlantic (NEA) was brokered on 12 March 2014. A five-year arrangement was reached between the EU, the Faeroe Islands and Norway (but not Iceland). The situation in 2016 is that the three parties agreed a total allowable catch (TAC) of 895,900 tonnes (shared 201,663 tonnes to Norway, 112,892 tonnes to the Faroe Islands and 441,586 tonnes to the EU) with an additional 15.6% nominally set aside for other unspecified countries (i.e. Iceland and Russia), although this is still highly contentious. Hughes *et al.* (2015) suggest that future models of catch sharing should not rely on previous understanding of mackerel distributional patterns in the literature, and that a more nuanced understanding of fleet dynamics will be necessary. Hannesson (2013) constructed a model to examine sharing of the Northeast Atlantic mackerel stock using 'game theory'. Responses were analyzed as a game between four parties: the European Union, Norway, the Faroe Islands, and Iceland. Consideration was given to the importance of the nature of the migration as a factor in determining the bargaining position of each of the parties. If the migration of the stock into a minor party's zone depends on stock abundance (density dependent expansion), as the case seems to be for the migrations of the mackerel into the Icelandic zone, the bargaining position of the minor player is weak. By choosing a high enough fishing mortality, the major players could theoretically reduce or altogether prevent the migrations of the stock into the minor player's zone and thus shut them out of the fishery (Hannesson, 2013).

As an added aside to the mackerel re-distribution story, MacKenzie *et al.* (2014a) reported that commercial boats targeting mackerel in waters east of Greenland have started catching bluefin tuna *Thunnus thynnus* for the first time. The presence of bluefin tuna in the north Atlantic is likely due to a combination of warmer water temperatures that are physiologically tolerable and immigration of an important prey species (mackerel) to the region. A parallel phenomenon has been reported off southwest England, where large schools of bluefin tuna were observed in 2015 and again in 2016, having been absent for many decades (Jeroen van der Kooij, Pers. Obs., and Mail Online, 21 August 2015).

Another persistent feature of MCCIP reports over the past 10 years has been the suggestion of increasing cephalopod (squid, cuttlefish and octopus) populations, and the often repeated statement that: "more boats are now trawling for squid than the region's traditional target species, such as haddock and cod," (originally from Hastie *et al.*, 2009). Since 2013, a number of high-profile research papers have been published that support this claim. Most notably, Doubleday (2016) assembled global time-series of cephalopod catch rates (catch per unit of fishing or sampling effort), and demonstrated that cephalopod populations have increased globally over the last six decades; a result that is remarkably consistent across a highly diverse set of cephalopod taxa. This study included many time-series from around the United Kingdom (survey data supplied by Cefas). A more detailed analysis by van der Kooij *et al.* (2016) extracted squid catches from a unique 35-year time-series of bottom trawl survey data in the North Sea (1980–2014); collected during late summer (August–September). Changes in distribution and abundance were compared with key climatic variables. Squid distribution across the North Sea increased over the 35-year time series. Significantly positive relationships were found between this increase and climate variables for each of the dominant individual taxa studied, and also when all species were combined. *Loligo* expanded southward from a predominantly north-easterly distribution, compared to northward expansions by *Alloteuthis* and the *Ommastrephidae* from their core distributions in the southern and central North Sea, respectively. In the Economics of Climate Resilience report commissioned by Defra in 2013, squid (*Loligo vulgaris*) distributions were projected to expand northwards by around 445 km over the next 40 years (habitat suitability in UK waters increasing by around 31%). Xavier et al. (2016) used similar models to predict distribution changes for European cuttlefish *Sepia officinalis*. These authors suggested that *S. officinalis* will continue to spread northwards and that it could eventually reach American shores by crossing the north Atlantic (via stepping-stones in Iceland and Greenland) from the UK, assuming future climate change.

The UK trade newspaper Fishing News included a special feature on expanding summer squid fisheries in the Moray Firth on 14th January 2016. This article stated that: *"It is probably fair to say that none of the trawlers fishing squid in the Moray Firth at the time of this trip were doing so out of choice. Rather, their presence was directly associated with the necessity to maintain some form of income when restrictions were preventing them from engaging in their preferred fisheries"*. Also that: *"The need to purchase customised squid trawls means that gearing-up for a fishery that usually lasts for just two months [each year], and sometimes considerably less, requires considerable initial outlay"*.

Over the course of the past 3 years (since the 2013 MCCIP report), a number of new high-level modelling reports have been published that offer real insights into future impacts of climate change on UK fisheries. Rutterford *et al.* (2015) used fish survey data, together with generalized additive models (GAMs), to predict trends in the future distribution of species in the North Sea, and concluded that fish species over the next 50 years will be strongly constrained by availability of suitable habitat, especially in terms of preferred depths. Shallow-water flatfish species may be particularly impacted since, if forced northwards by warming seas, suitable habitat will be greatly constrained, leading to a requirement for rapid ecological niche shifts, or else population declines. Jones *et al.* (2015) used similar models and suggested that the total maximum catch potential is projected to decrease within the UK Exclusive Economic Zone (EEZ) by the 2050s, resulting in a 10% decrease in net present value, assuming a 'high' emission SRES A2 scenario. Few studies have attempted to extend bioclimatic projections to assess the socio-economic impacts of climate-induced range shifts. This study links species distribution modelling with cost-benefit analyses. Despite the variation in predictions from alternative model formulations, the direction of change in net present value (NPV) proved to be robust to model choice. This study highlights many of the key factors influencing future profitability of UK fisheries and the importance of enhancing adaptive capacity (Jones *et al.*, 2015). Fernandes et al (2017) employed similar methodologies (see description below) and projected standing stock biomass decreases between 10 and 60%. These impacts translate into an overall fish and shellfish catch decrease of between 10 and 30% by 2020.

2.2 Physiological impacts of warming

Nephrops norvegicus (langoustine/scampi) remains the most important fishery species in Northern Ireland (6,900 tonnes in 2014, with a value of £14.8 million) and by far the most important shellfish species in Scotland (20,200 tonnes, £23.6 million). Since 2013, a number of new papers have emerged that offer insights into climate change impacts on this species in particular. Notably, several recent studies have reported results from laboratory experiments. Wood *et al.* (2015) investigated the effect of hypercapnia (low oxygen) and salinity stress on the early life stages of the *Nephrops*. This study demonstrated that environmental stressors have the potential to have a large effect on future recruitment. Similarly, Styf *et al.* (2013) studied the embryonic response of *Nephrops* to long-term exposure to ocean acidification (lowered pH) and elevated temperature. Berried female *Nephrops* were exposed to the combination of six ecologically relevant temperatures (5–18°C) and reduced pH (by 0.4 units). Embryonic responses were investigated by quantifying proxies for development rate and fitness including: % yolk consumption, mean heart rate, rate of oxygen consumption and oxidative stress. Increased temperature had positive effects on embryonic development, but no impact of lowered pH was detected for most embryonic development parameters (except the level of oxidative stress). The insensitivity of *Nephrops* embryos to low pH might be explained by adaptation to a pH-reduced external habitat and/or internal hypercapnia during incubation. These results thus indicate that this species could benefit from global warming and be able to withstand the predicted decrease in ocean pH in the next century during their earliest life stages (see similar results for other shellfish, below).

O'Sullivan *et al.* (2015) provided a novel modelling study of *Nephrops* metapopulation connectivity in waters around Ireland (including Northern Ireland) taking into account seawater temperatures. The authors employed hydrodynamic and larval transport models to describe spatial and temporal changes in oceanographic conditions, and to quantitatively predict the degree of connectivity between populations. Following spawning, *Nephrops* larvae are hatched into the water column, and the pre-zoea migrate vertically to the warmer surface layer, passing through three temperature-dependent stages of development. Temperature is particularly important in determining durations of each larval stage. This study found that increasing seawater temperature through May and June in the Irish Sea encouraged rapid larval development, resulting in increased larval viability and increased settlement as the season progressed. In addition, gyres are considered the classical retention mechanism for *Nephrops* larvae. Gyre speed and strength is primarily influenced by water temperature and seasonal stratification patterns. Neumann *et al.* (2013) use bioclimate envelope modelling techniques to predict habitat suitability for adult *Nephrops* in the North Sea. These authors did not project habitat suitability surfaces into the future assuming climate change, although this should be straightforward, given that similar techniques have been applied to other commercial fish and invertebrates (Defra, 2013).

Both theory and empirical observations suggest that warming and reduced oxygen will together act to reduce body size of marine fishes, as well as constraining distributional responses to climate change. Emphasis on physiology (a topic that had largely been out of fashion since the 1980s) has been increasing in recent years – mainly because of highly-cited studies such as Pörtner and Farrell (2008) and the perceived need to improve the reliability of modelling frameworks, thereby enhancing the quality of model projections (see Koenigstein *et al.,* 2016). This represents an important advancement; - understanding mechanisms and not merely correlating observed distribution patterns with habitat features (or winter NAO etc.). Cheung et al. (2012) developed a model to examine the integrated biological responses of over 600 species of marine fishes due to changes in distribution, abundance and body size. The model has an explicit representation of ecophysiology, dispersal, distribution and population dynamics. The authors showed that assemblage-averaged maximum body weight is expected to shrink by 14–24% globally from 2000 to 2050 under a high-emission scenario. About half of this shrinkage is due to change in distribution and abundance, the remainder to changes in physiology. This conclusion, which garnered global press coverage upon publication, has been challenged on the grounds that both the scale and the speed of the change are not credible (Brander *et al.*, 2013). Criticism of the projection model was subsequently refuted by the authors (Cheung *et al.*, 2013), but it has highlighted the need for 'ensembles' of different biological models, or at least more than one tool – to create increased confidence in projections. Koenigstein *et al.* (2016) provide a useful review of available modelling approaches for marine fish, analyzing their capacities for process-based integration of environmental drivers.

For the area around the British Isles in particular, Cheung *et al.* (2012) suggested a decline in mean assemblage maximum body weight (g) of around 20%. Baudron *et al.* (2014) have subsequently examined observational data and show that over a 40-year period (1970–2008) six of eight commercial fish species in the North Sea exhibited concomitant reductions in asymptotic body size, with the synchronous component of the total variability coinciding with a 1–2°C increase in water temperature. Smaller body sizes have decreased the yield-per-recruit of these stocks by an average of 23%. Although it is not possible to ascribe these phenotypic changes unequivocally to rising temperature, four aspects support this interpretation: (i) the synchronous trend was detected across species varying in their life history and lifestyle; (ii) the decrease coincided with the period of increasing temperature; (iii) the direction of the phenotypic change is consistent with physiological predictions; and (iv) no cross-species synchrony was detected in other species-specific factors potentially impacting growth. These findings support the contentions of Cheung *et al.* (2012) that fish size will shrink in response to climate-induced changes in temperature and oxygen.

2.3 Effects on recruitment

A consistent feature of MCCIP reports over the past 10 years has been a focus on climatic impacts on recruitment (i.e. the number of juvenile fish reaching an age or size whereby they can be caught or counted in nets). Since 2013, a number of new publications have appeared that provide insights of relevance to UK commercial species. Ottersen *et al.* (2013) examined the effects of variation in spawning stock and sea temperature on long-term temporal patterns in recruitment dynamics of 38 commercially harvested fish stocks in the northern North Atlantic. For half of the stocks studied, the temperature effect was statistically significant when added to the model of the relationship between recruitment success and spawning stock biomass. This included all six of the herring stocks studied, with a positive effect for cold-water stocks and negative effect for stocks in the more temperate southern areas (including the west of Scotland and North Sea). For the various plaice stocks, a tendency was found toward recruitment being favoured by lower temperatures. This is consistent with what has earlier been documented by Fox *et al.* (2000), who further pointed to temperature during the first months of the year being of particular importance by affecting predation pressure on the planktonic stages of plaice and subsequently their recruitment.

Pécuchet *et al.* (2015) investigated the potential impacts of various abiotic and biotic factors on the recruitment strength and variability of North and Baltic Sea stocks. Stock-recruitment models were fitted for the different fish stocks using recruitment (R) and spawning-stock biomass (SSB) from ICES stock assessment working groups. The percentage of survival explained by different environmental variables (e.g. temperature, salinity, nutrients, currents), varied between 9.5% for western Baltic Sea sole (*Solea solea*) and 89.1% for North Sea whiting (*Merlangius merlangus*). For 15 of the 18 stocks studied, >50% of the deviance was explained by environmental variables. The most frequent explanatory variables were current speed (which was present in the final model for 13 of 18 stocks), fish stock biomass (10 of 18) and salinity (9 of 18). The salinity variable was present in eight of the ten Kattegat–Baltic Sea stocks, except the sprat and sole, but was completely absent in the final model for every North Sea stock except sprat. For North Sea cod and sole (but not plaice, whiting, haddock and saithe *Pollachius virens*), water temperature was an important influence.

Beggs *et al.* (2014) examined links between climate and Irish Sea cod recruitment during a period of declining spawning stock biomass (SSB). Specifically, the authors tested for a shift in the relationship between recruitment, SSB and climate by comparing an additive (generalized additive model, GAM) and non-additive threshold model (TGAM). The relationship between recruitment success, SSB and the climatic driver sea surface temperature, was best described by the TGAM, with a threshold identified between recruitment and SSB at approximately 7,900 t. The analysis suggests a threshold shift in the relationship between recruitment and SSB in Irish Sea cod, with cod recruitment being more sensitive to climatic variability during the recent low SSB regime. Ottersen *et al.* (2013) found that threshold models performed better than the best linear or nonlinear stationary models for 27 of the stocks they examined, suggesting that abrupt changes (potentially even regime shifts) may be commonplace.

The North Sea cod stock declined over the past four decades, linked with previous overfishing and climate change. Changes in stock structure due to overfishing have made the stock largely dependent on its recruitment success which, in turn, greatly relies on environmental conditions. Nicolas *et al.* (2014) tested whether observed changes in the distribution of recruits in the North Sea could be related to direct (i.e. temperature) and/or indirect (i.e. changes in the quantity and quality of zooplankton prey) effects of climate variability. The analyses were based on spatially resolved time series: i.e. sea surface temperature (SST) and zooplankton records from the Continuous Plankton Recorder Survey. The authors showed that spring SST increase was the main driver for the most recent decrease in cod recruitment, although the late 1990s were also characterized by relatively low total zooplankton biomass, particularly of energy-rich zooplankton such as the copepod *Calanus finmarchicus*, which have further contributed to the decline in recruitment of North Sea cod. All of these studies suggest ‘bottom-up’ impacts on cod recruitment, however, top-down processes such as predation are poorly studied. A recent study by Akimova *et al.* (2016) showed how changes in temperature influence cumulative mortality of cod through the early juvenile period, and several authors have suggested that the proliferation of certain predators, sometimes as a result of climatic influences, may have influenced the apparent slowness of recovery in the cod stock of the North Sea (e.g. Kempf *et al.,* 2013).

2.4 Ocean Acidification (OA)

Over the past few years many hundreds of papers have been published focussing on the impacts of ocean acidification (Browman, 2016). However, there is still a lack of conclusive evidence as to what the possible consequences for fish and shellfish might be and, consequently, the impacts on commercial fisheries are largely unknown. Opinions voiced in the literature range from complete catastrophe for global fisheries (e.g. Colt and Knapp, 2016) to very modest impacts. Several modelling papers have emerged as a result of the recently completed UK Ocean Acidification Research Programme (jointly funded by NERC, Defra and DECC) and the parallel German BIOACID programme.

In a UK study by Fernandes *et al.* (2017), available observational, experimental, and modelling approaches were combined to quantify potential impacts of ocean acidification and warming on future fisheries catches, as well as revenues and employment in the UK fishing industry under different CO_2 emission scenarios. Across all scenarios, based on sparse but currently available experimental results, bivalve species were suggested to be more affected by ocean acidification and warming than the fish species, when compared to impacts of ocean warming alone. Projected standing stock biomasses decreased between 10 and 60%, depending on the particular assumptions. These impacts translate into an overall fish and shellfish catch decrease of between 10 and 30% by 2020 across all areas except Scotland for >10 m fishing fleet. Only this Scottish fleet showed average positive impacts, but those were lost after 2050. The main driver of the projected decreases is suggested to be increases in temperature (+0.5–3.3°C), which exacerbate the impact of decreases in primary production (10–30%) in UK fishing waters. The inclusion of the effect of ocean acidification on the carbon uptake of primary producers (phytoplankton) had very little impact on the projections of potential fish and shellfish catches (<1%).

The validity of assumptions with regard to ocean acidification in this study by Fernandes *et al.* (2017) can be considered somewhat ‘heroic’ and included: slight changes in body mass (size) and adult natural mortality for cod; changes in larval natural mortality for seabass; changes in growth rate, size, mobility and natural mortality for scallops and cockles; and changes in adult mortality for mussels (Fernandes et al., 2017; largely based on outputs of recent meta-analyses, e.g. Kroeker et al., 2013). However, many experimentalists working on exactly the same species (e.g. scallops) in the laboratory have found no effect (see below), and limited sensitivity to changes in pH, hence we need to be cautious in our interpretation of the model results. Overall, Fernandes et al. (2017) suggested that losses in revenue were estimated to range between 1–21% in the short term (2020–2050), with England and Scotland being the most negatively impacted region in absolute terms and Wales and North Ireland in relative terms. Losses in total employment (fisheries and associated industries) may reach approximately 3–20% during 2020–2050 with the >10 m fleet and associated industries bearing the majority of the losses.

Narita and Rehdanz (2017) attempted to perform a national and sub-national assessment of the economic impact of OA on mollusc production in Europe. These authors focus on mollusc production because the scientific evidence on the biological impact on calcifying organisms was considered ample relative to other types of marine organisms. In addition, Europe and its regions are significant producers of marine molluscs. This work complements earlier and ongoing UK-specific work reported in the UK Climate Change Risk Assessment (CCRA) by Pinnegar *et al.* (2012). Highest levels of overall impact were found in the countries with the largest current shellfish production, such as France, Italy and Spain. Narita and Rehdanz (2017) examined impacts in the United Kingdom, the Channel Islands and the Isle of Man. The authors assumed two scenarios of biological sensitivity based on Kroeker *et al.* (2013), i.e. the value of calcification loss (40%, the largest effect size) and the value of growth loss (17%; the smallest effect size). This is likely to be an oversimplification, but scientific information is lacking regarding the different levels of impact appropriate across different species of commercial importance (Hilmi *et al.*, 2014).

Narita and Rehdanz (2017) suggest that annual economic losses in the United Kingdom, the Channel Islands and the Isle of Man by 2100 could amount to US$ 97.1 million, US$ 1 million and US$ 12.7 million respectively under a worst-case scenario (figure 1), mostly due to impacts on scallop fisheries. The authors also provided annual economic losses for sub-national regions in Europe as a result of damage to mussel and oyster culture specifically. This highlighted that Wales and Northern Ireland are the most susceptible of the UK regions to damage to mussel culture, whereas southwest England is most susceptible in terms of lost oyster production, although nowhere near as vulnerable as regions in France.

Sanders *et al.* (2013) examined the impact of elevated CO_2 concentrations (reduced pH) on oxygen consumption, food clearance rates and cellular turnover in juvenile king scallop *Pecten maximus*. This species supports very important fisheries in Wales and in the Isle of Man (where it is the most important resource, accounting for 2,345 tonnes and £4.5 million in 2015). None of the experimental exposure levels (290, 380, 750 and 1140 µatm) were found to have significant effects on scallop growth or metabolism, following 3 months laboratory exposure. While it is clear that some life stages of marine bivalves appear susceptible to future levels of ocean acidification, particularly under food limiting conditions, the results from this study suggested that where food is in abundance, juvenile *P. maximus* may display tolerance. Similarly, Mackenzie *et al.* (2014) examined the effects of near-future pH (ambient pH -0.4 pH units) and warming (ambient temperature +4°C) on the shells of the mussel *Mytilus edulis* in the UK. After six months exposure, warming, but not acidification, significantly reduced shell strength. The maintenance of shell strength despite seawater acidification suggests that biomineralisation processes are unaffected by the associated changes in $CaCO_3$ saturation levels. These authors concluded that under near-future climate change conditions, ocean warming will pose a greater risk to shell integrity in *M. edulis* than ocean acidification, even when food availability is limited.

Recent experiments on larvae and juveniles of European lobster *Homarus gammarus* (Agnalt *et al.*, 2013; Small *et al.*, 2015) showed no clear effects of pCO_2 treatment on either carapace length or dry weight, although deformities were more commonly observed. The proportion of larvae with deformities increased with increasing pCO_2 exposure, independent of temperature. In the medium treatment about 23% were deformed, and in the high CO_2 treatment about 43% were deformed (Agnalt *et al.*, 2013). Small *et al.* (2015) showed no significant effect of elevated pCO_2 on cumulative survival, although survival of larvae from stage I to stage II significantly decreased at higher temperatures. Similarly, there were no significant effects of pCO_2, in isolation or in consort with temperature, on growth and morphometrics. There were, again, no significant effects of elevated pCO_2 on the rates of oxygen consumption at larval stages I, II and III. At larval stage IV however, the rates of oxygen consumption were significantly higher at 1,100 µatm pCO_2 than at 420 µatm pCO_2, but the significance of this observation is poorly understood. Carapace magnesium content increased significantly as temperature increased under 420 µatm pCO2 but not under 1,100 µatm pCO_2. Decreases in carapace mineralization have previously been demonstrated for larval stage IV lobsters (Arnold *et al.*, 2009).

2.5 Storminess

At present, confidence in the wind and storm projections from Global Climate Models (GCMs) and down-scaled Regional Climate Models (RCMs) is relatively low, with some models suggesting that northwest Europe will experience fewer storms in the future whereas other models suggest an increase in storminess. The winter of 2013/14 was identified as one of the stormiest (in terms of wind speeds, wave heights, etc.) of the past 66 years (Matthews *et al.*, 2014). The UK fishing industry was severely disrupted during this period, with many vessels tied up in port for at least five months, along with severe damage to fishing boats and harbour facilities (Andrew, 2014). The lack of fish reaching markets resulted in significantly higher prices nationally and in April 2014 the MMO launched a “Storm Damage Gear Replacement Scheme” supported by the European Fisheries Fund (EFF).

Climate change, through its influence on storm conditions can impact the performance of fishing vessels or gears, the behaviour of the fish themselves, as well as safety and stability of vessels at sea. However very little research has been carried out on this topic, and so we have low confidence in projections about the future. Morel *et al.* (2008) examined the decision-making process of commercial fishing skippers operating in the Celtic Sea (off southwest Ireland), by interviewing 34 fishermen and examining trade-offs between safety and production goals. The results suggested that the information skippers receive from the shore (e.g. weather forecasts, market price of fish) are vitally important determinants of their decisions about whether or not to go fishing. Contrary to the results expected, fishing skippers did not choose to stop fishing during poor weather but, rather, adopted a strategy aimed at maximising performance. Of the 34 skippers, 25 chose to leave a fishing zone because they hoped to increase their catch elsewhere, and 8 decided to seek shelter, not so much because of rough weather but because of the expectation of lower catches.

A study of perceived risks in the Northern Ireland fishing industry (Booth and Nelson, 2014) examined views and the decision-making process of 40 active fishermen based at Portavogie harbour. Respondents were asked to rank and

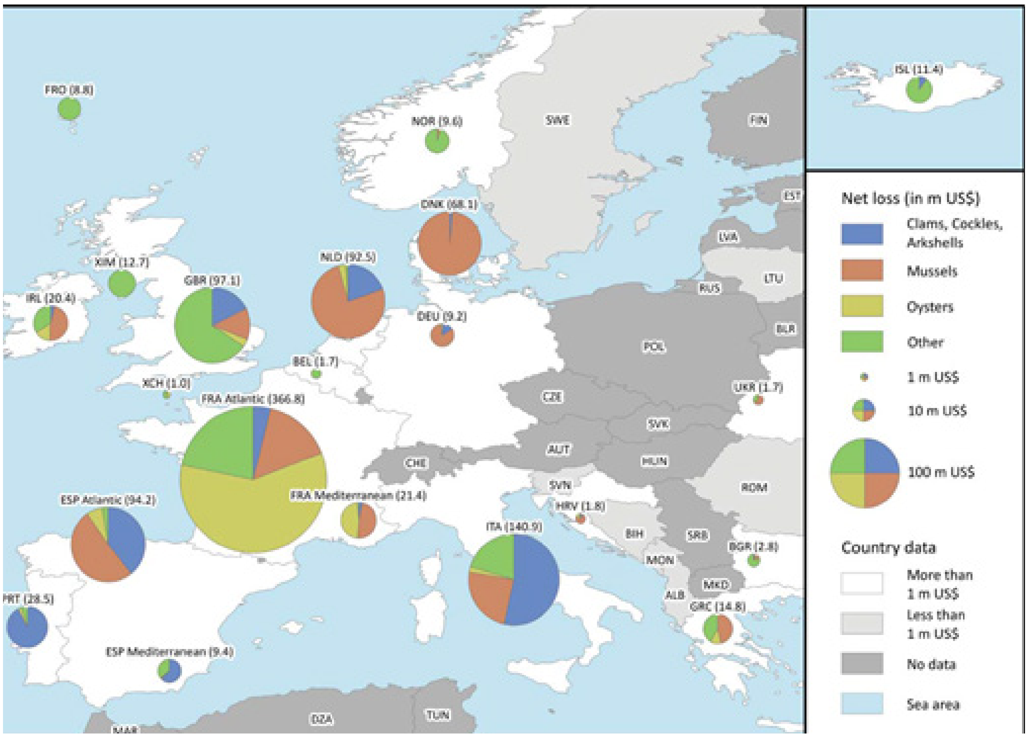

Figure 1. *Estimated annual economic loss in Europe in the year 2100 due to damage on mollusc production under ocean acidification for selected species groups (parteq_calci_V scenario). From Narita and Rehdanz (2017).*

score 12 risk items. Those items listed as causing greatest concern to fishermen's livelihoods included fuel costs, quota restrictions and drowning, whereas more remote issues such as global warming had considerably less resonance. Some of the risk factors that scored highly (e.g. 'drowning' or 'cold/hypothermia') were undoubtedly linked to weather conditions and hence climate, but were not articulated as such.

Notably, a December 2015 report written by Seafish (Garrett *et al.*, 2015) included a number of 'Industry perspectives on climate change'. These highlighted that: "*taking action to adapt to [long term] climate change is not presently a priority for the majority of industry contributors. Industry [instead], highlight the effect of near term events – severe storms affecting ports in Fraserburgh and Peterhead and in the South West, stormy conditions affecting crew safety, flooding of processing units, changing distribution of species for example — particularly in the domestic context*".

3. HOW OUR UNDERSTANDING HAS DEVELOPED OVER THE PAST DECADE?

3.1 Where have early concepts/predictions been borne out?

Ever since the first MCCIP report card was published in 2006, European seabass *Dicentrarchus labrax* have been held up as a 'poster child' of marine climate change in the UK – with an expectation that populations would increase dramatically in the future and that distributions of this warm-water fish species would continue to expand northwards. Evidence suggests that populations, especially in the Channel, did expand dramatically in the early years (Pawson *et al.*, 2007), and that seabass were indeed expanding northwards. Commercial catches increased dramatically during this period and recruitment was consistently high (figure 2). However, in recent years, fishing mortality has reached unsustainable levels (fisheries expanded at too fast a rate), such that recruitment success has apparently been damaged (not enough spawning adults to maintain the population); also a few cooler winters (in 2009/10 and 2010/11) seem to have halted the expansion, and stocks have begun to decline (figure 2). Seabass are not subject to EU TACs and quotas, therefore, fisheries were largely allowed to expand with impunity. Consequently, in 2016 very draconian measures were introduced in order to control fishing effort, even impacting on recreational fisheries. These measures include: (1) complete closure throughout 2016 to all commercial seabass fishing west of Ireland; (2) from 1 January to 30 June, a six-months prohibition on commercial fishing for seabass in the North Sea, Irish Sea, English Channel, and Celtic Sea; (3) from 1 July to 31 December 2016 monthly catch limits to all commercial vessels; (4) from 1 January to 30 June 2016 recreational catch and release only; (5) from 1 July to 31 December 2016 one seabass per recreational fisherman per day. Seabass have undoubtedly been observed further north than was previously the case, although, because of overfishing, not in the numbers originally anticipated.

Similarly, a recurrent theme in the 'fish' and 'fishery' supporting documents for MCCIP over the past ten years has been expanding populations of European anchovy *Engraulis encrasicholus* in the North Sea and English Channel and associated concerns about quota allocation among countries and access to these burgeoning fishery resources. Beare et al. (2004) were among the first to document the expansion of anchovy, showing that this species was almost totally absent from the North Sea until the mid 1990s, although small numbers had occasionally and sporadically been caught, e.g. in the mid 1970s (a relatively warm period). Numbers increased dramatically after 2000 and the species was widely distributed (over almost 80% of the International Bottom Trawl Survey area), except in the most northern and western regions. Future projections such as those of Defra (2013) anticipated that anchovy would continue to expand northward by ~320km over the next 50 years, and that the UK Exclusive Economic Zone (EEZ) would become significantly more 'suitable' as a result of climate change in the future. In

2013, Petigas *et al.* concluded that anchovy in the southern North Sea (including the Thames estuary) are most likely a distinct remnant sub-stock that has always been present, but are now benefiting from greatly improved environmental conditions rather than an invasion of animals from further west (i.e. the Bay of Biscay). This is important politically as according to the rules of 'relative stability' within the EU Common Fisheries Policy (CFP), Spanish and French vessels would not be granted exclusive access to this resource, unlike as is presently the case in the Bay of Biscay. Since 2012 fishery landings from the Channel and North Sea regions have remained relatively low, but also highly variable with mostly British and French vessels taking ~760 tonnes of anchovy in 2014, following several successive years with lower catches. Raab *et al.* (2013) used models and empirical data to explore the effects of temperature and food availability on the adult anchovy population across the North Sea. Temperature explained the distribution and abundance of anchovy in the North Sea better than food availability or a combination of both environmental factors.

Changes in fish distribution patterns (including seabass and anchovy) have featured in all of the MCCIP report cards, and the evidence base of observations and model outputs has grown steadily throughout the 10 years that MCCIP has been in existence. In 2006, the original 'fish and fisheries' supporting document (Pinnegar, 2006) made reference to the now highly-cited paper published in *Science* by Perry *et al.* (2005). This study demonstrated that distributions of both exploited and non-exploited North Sea fishes had responded markedly to recent increases in temperature, with nearly two-thirds of species shifting in mean latitude over 25 years. Following publication of this ground-breaking work by Perry *et al.* (now cited >1,600 times) many additional studies have been published that have confirmed shifts in distribution around the United Kingdom. These have included observational studies that have made use of scientific survey datasets (e.g. Dulvy *et al.*, 2008; Hiddink and ter Hofstede, 2008; Lynam *et al.*, 2010; Simpson *et al.*, 2011; Montero-Serra *et al.*, 2015), but also studies that have examined data from commercial fisheries and demonstrated shifts in catch-per-unit-effort (e.g. Heath 2007; Engelhard *et al.*, 2011, 2014). Many of the studies published since 2006 have demonstrated that the situation is not simply a case of species shifting distributions 'northwards' (Pinksky *et al.,* 2013), but that there is also a strong interaction with patterns of fishing pressure as well as depth. In an analysis of 50 abundant demersal species in the waters around UK and Ireland, 70% were shown to have responded to warming in the region by changing distribution and abundance (Simpson et al., 2011). Specifically, warm-water species with smaller maximum body size have increased in abundance while cold-water, large-bodied species have decreased in abundance. For pelagic fish species, a recent paper by Montero-Serra *et al.* (2015) investigated patterns of change using records from 57,870 fisheries-independent survey trawls across the

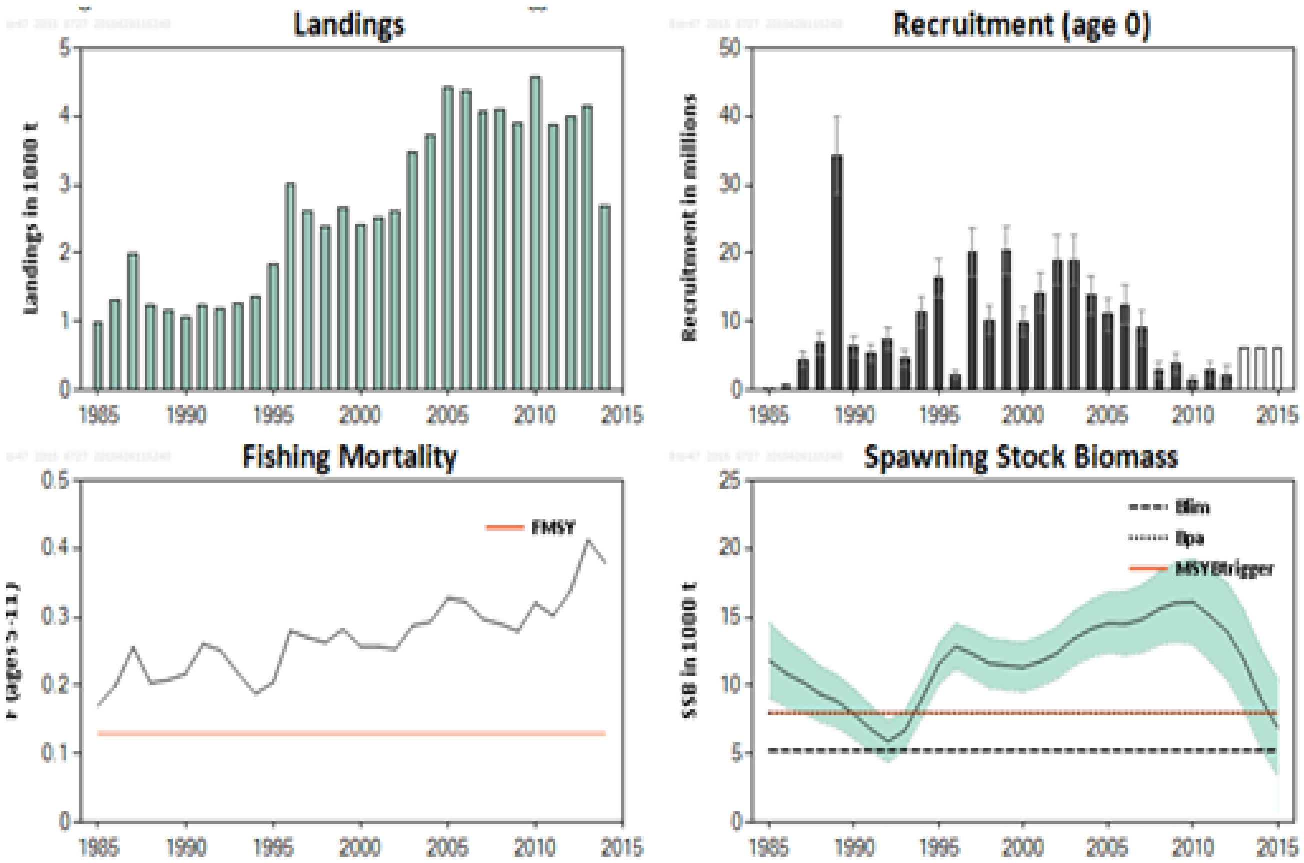

***Figure 2**: Seabass in in the southern North Sea, Irish Sea, English Channel, and Celtic Sea. Summary of stock assessment (weights in thousand tonnes). Landings are from the commercial fishery only. Fishing mortality is shown for the combined commercial and recreational fisheries (ICES 2015a).*

European continental shelf between 1965 and 2012. These authors noted a strong 'subtropicalization' of the North and Baltic Seas. These areas have shifted away from cold-water assemblages typically characterized 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 driver of change in these species has been sea surface temperatures in all cases (Montero-Serra *et al.*, 2015).

Perry *et al.* (2005) noted that certain warm-water species seem to have shifted their distribution southwards over the past few decades (i.e. in the opposite direction to what might generally be expected in the northern hemisphere). This was confirmed by Engelhard *et al.* (2011) for sole in the North Sea and also for scaldfish *Arnoglossus laterna*, solenette *Buglossidium luteum* and bib *Trisopterus luscus* (Dulvy *et al.*, 2008). Cold winters are known to have coincided with mass die-offs of sole in the past, with this species migrating offshore each winter to the central North Sea in order to avoid excessively cold conditions near the coast (e.g. Woodhead, 1964). 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 of some warm-water commercial fish (Engelhard *et al.*, 2011).

Dulvy *et al.* (2008) reflected on the earlier findings of Perry *et al.* (2005) and explored the year-by-year distributional response of the North Sea demersal fish assemblage in response to climate change. These authors found that the whole North Sea fish assemblage had deepened by ~3.6 m per decade since 1981 and that the deepening response was far more significant in comparison with the latitudinal response that had previously been reported based on the same data (Perry *et al.*, 2005). A recent paper by Freitas *et al.* (2015) combining 4 years of telemetry-derived behavioural data on juvenile and adult (30–80 cm) Atlantic cod (*Gadus morhua*), and in situ ocean temperature measurements, found a significant effect of sea temperature on cod depth use and activity level in the coastal Skagerrak. During summer and in periods when sea surface temperature increased, cod were found in deeper waters. The authors of this study reasoned that future and ongoing rises in sea surface temperature may increasingly drive cod away from shallow feeding areas during summer, which may be detrimental for local populations of the species.

For many years it has been argued (including in various MCCIP reports) that cooler-water species such as cod, might not be able to persist around the UK in the future, if seawater temperatures continue to rise. Indeed, Drinkwater (2005) predicted, on the basis of correlations between temperature and recruitment, that cod stocks in the Celtic and Irish Sea are expected to disappear altogether by 2100, while those in the southern North Sea will probably decline. Cook and Heath (2005) also examined the relationship between sea surface temperature and recruitment in a number of North Sea fish species (cod, haddock, whiting, saithe, plaice, sole). These authors concluded that if the recent warming period were to continue, stocks that 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 by Cook and Heath (2005) suggest 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.

According to the most recent stock assessments for cod around the UK (ICES, 2015a), stocks were heavily overfished in the early-mid 2000s and populations were at their lowest ever recorded value (e.g. figure 3). However, since this period, fishing mortality has been significantly reduced through vessel decommissioning schemes and statutory effort controls. Spawning stock biomass in the North Sea has marginally recovered to a level above its precautionary reference limit (figure 3), but this recovery has been very slow. In the Irish and Celtic Seas, as well as the west of Scotland, cod stocks are still at low levels. Despite the very dramatic and deliberate reduction in fishing mortality, cod stocks have not yet attained the levels recorded in the 1970s, and this is largely a reflection of continued poor recruitment in all UK cod stocks, probably related to prevailing climatic conditions since the mid-1990s (e.g. figure 3, but also similar results for the west of Scotland, Irish Sea, Channel and Celtic Sea cod stocks).

It is interesting to note that events of the past 10 years (since publication of the first MCCIP report card) have largely followed the trajectories predicted by Kell *et al.* (2005), who 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. In these simulations the length of time needed for the cod stock to recover was not greatly affected by the particular climate scenario chosen (generally around five to six years), however, overall productivity was impacted and spawning stock biomass (SSB) once 'recovered' was projected to be considerably less given climate change than would have been the case assuming no temperature increase.

Another common theme that has been covered repeatedly in MCCIP 'fisheries' reports over the past 10 years has been 'phenology' (i.e. changes in the timing of natural events), such as fish spawning dates, migration patterns, emergence of larvae, etc. By 2006, many papers had been written about changes in the north Atlantic zooplankton community and possible consequences for commercial fish species (e.g. Beaugrand *et al.*, 2002, 2003). 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). However, since the first MCCIP 'fisheries' report (Pinnegar, 2006), many new papers have emerged that provide more detail on this phenomenon, including changes over the past decade.

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 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. A clear seasonal shift to earlier appearance of fish larvae has been described for southern North Sea cod and many other species (Greve *et al.*, 2005). In the English Channel, earlier spawning following warmer temperatures has been observed in summer (July to September) spawning species, for example mackerel and horse mackerel (Genner *et al.*, 2010). In contrast, species that spawn in spring tend to spawn later following warmer winters, including lemon sole *Microstomus kitt* and pollack *Pollachius pollachius* (Genner *et al.*, 2010).

The past 10 years have witnessed unprecedented warmth of the seas around the British Isles (ICES IROC, 2014), but also a number of noteworthy discrete events that have impacted on commercial fish stocks. Despite the general trend of increasing mean seawater temperatures, several winters were relatively cool and are thought to have benefitted recruitment in certain cold-water species, notably in 2009/10, 2010/11 and 2011/12. However, 2014 witnessed a resumption of

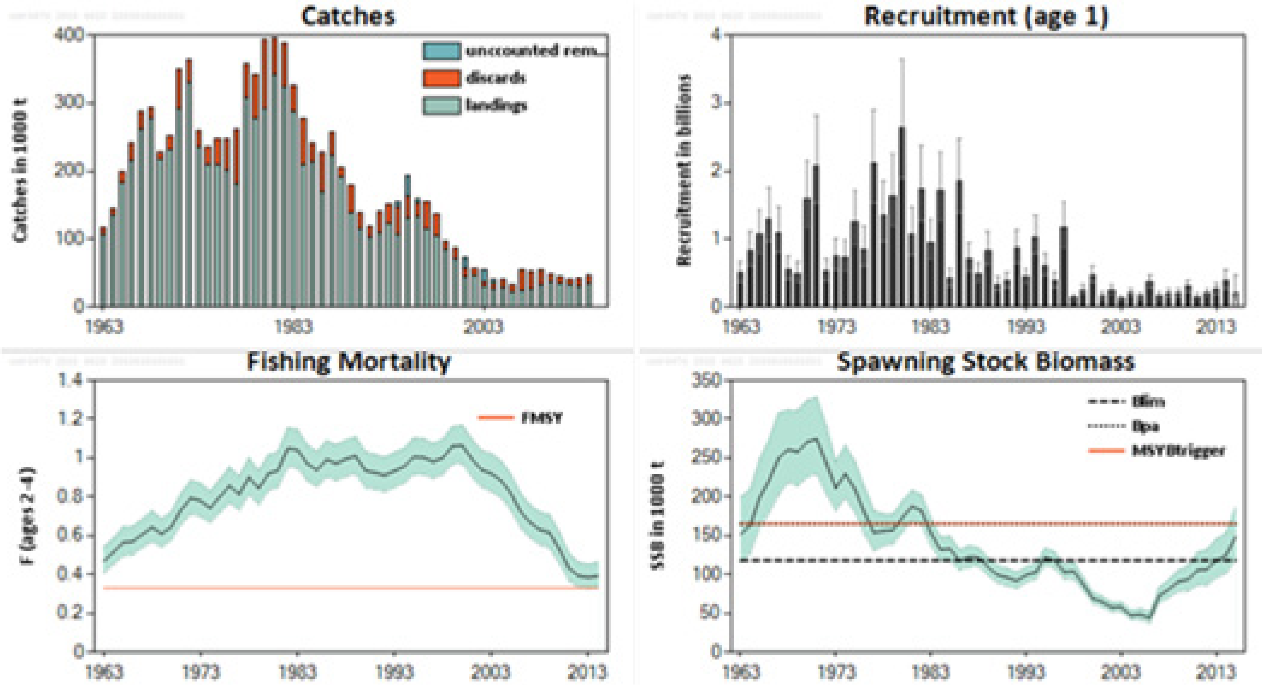

Figure 3. *Cod in the North Sea, eastern English Channel and Skagerrak. Summary of stock assessment with point-wise 95% confidence intervals (ICES, 2015b). Any observed changes over the past decade, including any extremes.*

record high air temperatures throughout the eastern North Atlantic and this was reflected in record high sea surface temperatures in the North Sea. In 2015, the UK mean air temperature was 9.2°C; 0.4°C above the 1981–2010 long-term average. New UK air temperature records of 36.7°C and 22.4°C were set on 1 July and 1 November 2015, respectively. While November was very mild, December was the mildest December in England since 1659. Very low recruitment was observed in 2014 and 2015 for North Sea cod, haddock and autumn-spawning herring.

The winter of 2013/14 was identified as one of the stormiest of the past 66 years (Matthews et al., 2014; Masselink et al., 2016) and during this period the UK fishing industry was severely disrupted. For England and Wales, this was also one of the most exceptional periods of winter rainfall in at least 248 years. As yet, there is no definitive conclusion as to the possible contribution of climate change to the recent weather events; this is in part due to the highly variable nature of UK weather and climate.

3.2 Variability in the context of longer term 'climatic' timeframes

Correlations have been identified between fish recruitment and many different climate variables, including sea surface temperature (SST), winter North Atlantic Oscillation (NAO) and the Atlantic Multi-decadal Oscillation AMO. The poor long-term predictability of these latter two climatic indices has greatly hampered efforts to accurately project climate impacts on commercial fish stocks, both in the near-term and over the next 50–100 years. A number of publications describing the impact of climate variability on small pelagic fish such as Atlantic herring, anchovy or sardine in the North Sea have been published (e.g. Gröger *et al.*, 2010; Alheit *et al.*, 1997; Pitois *et al.*, 2012; 2015). Pitois *et al.* (2015) detected a weak positive correlation between mackerel larvae abundance in the North Sea and the winter NAO. Other authors (see above) have linked the recent expansion of mackerel populations westwards towards Iceland and the Faroe Islands with positive phases of both the NAO and AMO. Goikoetxea and Irigoien (2013) suggested a link between European hake *Merluccius merluccius* recruitment and the AMO, whereby higher productivity in the hake stock in recent years may have been sustained (despite intense fishing pressure) due to highly conducive climatic conditions, including warmer temperatures.

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 tend towards slightly positive (on average) in the future due to increases in greenhouse gas emissions. Consequently, we might expect a slight tendency towards enhanced recruitment and larval abundance of species such as mackerel, herring, hake and anchovy in the future if the relationships observed in the past continue to hold.

Major advances over the last decade in oceanographic observation and modeling systems have led to unprecedented developments in the quality of information available to marine science. While improvements in observational technologies and networks have garnered much attention, remarkable developments in forecasting the ocean have received much less focus. The potential for predicting the ocean climate far exceeds that of the atmosphere. The slow-dynamics (and therefore "long-memory") of the ocean mean that anomalies can persist for months or longer and may sometimes be used as the basis for simple forecasts of potential relevance to fishery management.

Studies using both coupled atmosphere–ocean models and empirical statistical models have begun to demonstrate the potential for climate predictions on decadal time scales, particularly in the North Atlantic region. Progress can be seen in the retrospective multiyear forecasts of North Atlantic Ocean characteristics by Hazeleger *et al.* (2013), which skilfully predict variability associated with the Atlantic Multidecadal Oscillation 2–9 years ahead. The move from assessing the potential for decadal scale predictions to making experimental forecasts is also becoming possible. For example Smith *et al.* (2007, 2013) present the first climate prediction of the coming decade made with multiple models. These authors suggest that the AMO will remain positive for the rest of this decade. Matei *et al.* (2012) also show that the sea surface temperature (SST) variations of the North Atlantic and Mediterranean Sea can be skilfully predicted up to a decade ahead, and that the North Atlantic subpolar gyre region stands out as the location with the highest predictability.

In September 2016, a special theme session at the ICES Annual Science Conference focussed on "Seasonal-to-decadal prediction of marine ecosystems: opportunities, approaches, and applications", following a similar workshop at Princeton University in June 2015 on "Application of Seasonal to Decadal Climate Predictions for Marine Resource Management". It is hoped that within the next few years, 'near real-time' forecasts (3–5 year lead in times) will become available for climatic conditions around Europe, thus making it conceivable that these could be used by fishery scientists to generate short-term stock forecasts, and to set appropriate multi-year management goals. Many of the scientists working on this topic are part of the EU NACLIM project (Hátún and Payne, 2014), and early outputs have tended to focus on pelagic fishes such as blue whiting, with strong links to the North Atlantic subpolar gyre (e.g. Payne *et al.*, 2012).

3.3 What are future projections telling us now (vs. what we thought a decade ago)?

As stated above, many of the projections made a decade ago (e.g. Cook and Heath, 2005; Drinkwater, 2005; Kell *et al.*, 2005) have now been validated with additional observational evidence, and the overall story of impacts on fish recruitment or on distribution remains largely the same. However, one topic that received very scant attention in 2006 was the potential impacts of ocean acidification (OA) on commercial fisheries, as this pre-dated the expansion in scientific endeavour that was largely prompted by publication of the Royal Society report "Ocean acidification due to increasing atmospheric carbon dioxide" in June 2005.

There is still considerable uncertainty with regard to OA impacts on fish and shellfish (see above), however it is now becoming clearer as to what might happen locally in terms of projected changes in pH and carbonate saturation. In the Regional Ocean Acidification Modelling (ROAM) project of the recently completed UK Ocean Acidification Research Programme (UKOA), a coupled physical-ecosystem model was used to project future values for pH and aragonite saturation state for the North Western European Shelf (see Ostle *et al.*, 2016). The model was forced with data representative of the IPCC AR5 RCP 8.5 scenario, as simulated by the UKMO HADGEM model. The model suggests a clear decrease in both pH and saturation state around the UK, with areas along the south coast of Norway showing the strongest decrease in the future. Surface waters will gradually start to become under-saturated from around 2030 and more rapidly from 2080. By the end of the century, the model estimates that an area of surface water of approximately 300,000 km2 could become under-saturated, which could conceivably have major consequences for commercial fish and shellfish. The pH trends estimated from this model for OSPAR regions II (Greater North Sea) and III (Celtic Seas) are -0.0036 and -0.0033 pH units per year respectively (see Ostle *et al.*, 2016).

Another major uncertainty with regard to future projections for UK fisheries is the lack of clear consensus as to whether or not primary production (phytoplankton) will increase or decrease in the waters around the British Isles. Net primary production is a key driver of many ecosystem models. Recent variants of the bioclimate envelope approach (Cheung et al., 2011, 2013) suggest a reduction in maximum fisheries catch potential by up to 30% in the North Sea by 2050, relative to 2000 under the SRES A2 emissions scenario. In contrast, using a size-structured food web model Blanchard et al. (2012) predicted a 24% increase in potential catch for the UK, using the same underling climate scenario. Possible reasons for the discrepancy could be different underlying assumptions about changes in net primary production that drove the two contrasting biogeochemical models. The model used by Cheung *et al.* (2011) anticipated a decrease in net primary production available for fish while the one used by Blanchard *et al.* (2012) projected an increase.

Most recent studies (e.g. Jones *et al.*, 2015; Fernandes *et al.*, 2017) [see above] have used outputs from down-scaled regional models that anticipate a decline in net primary production. Consequently, these studies also suggest an overall decline in the net present value of fisheries in the UK. Jones *et al.* (2015) in particular used outputs from two different Earth system models (GFDL ESM2.1 and Medusa), both of which suggested declines in primary production for the northeast Atlantic. Opposite trends, however, were suggested in a study by van Leeuwen *et al.* (2016) who applied a coupled marine water column model to three sites in the North Sea. The model consisted of a hydro-biogeochemical model (GOTM-ERSEM-BFM) coupled one way upwards to a size-structured model representing pelagic predators and detritivores (Blanchard *et al.*, 2009). At all three sites (North Dogger, Oyster Grounds, Southern Bight), net primary production was projected to increase under a scenario of warming seawater temperatures, due to faster recycling of nutrients and a lengthening of the growing season. However, increased planktonic biomass actually led to a decrease in planktonic food supply for fish as the increases were largely limited to inedible functional groups (dinoflagellates and Phaeocystis colonies). Diatoms, the most important food for zooplankton and hence for fish, were projected to decrease at all three sites, but the rise in ambient water temperatures also increased growth rates at higher trophic levels, resulting in higher biomass for both fish and detritivores despite the minor decrease in planktonic food supply. Fish yields increased accordingly.

3.4 Any regional variations in impacts across the UK marine environment (coastal or marine)

It is anticipated that climate change (and ocean acidification) could have very different consequences for different regions or nations of the UK. Some insight into regional variations have been provided by Narita and Rehdanz (2017) and Fernandes *et al.* (2017) [see above] and will largely depend on the sensitivity of the primary target species in each locality. In England the top three fishery species, in terms of value, are scallops, edible/brown crabs *Cancer pagurus* and lobsters, whereas the top three fishery species in Scotland are mackerel, *Nephrops* and haddock. In Wales, the most valuable species are scallops, whelks and lobsters and in Northern Ireland *Nephrops*, scallops and mackerel provide most of the fisheries revenues (MMO, 2015). All of these species are known to be sensitive to warming temperatures and/or ocean acidification to some extent. In the Isle of Man, the main fishery species in terms of value are king scallop *Pecten maximus*, queen scallop *Aequipecten opercularis* and lobsters (MMEA, 2013). In Guernsey, the most valuable species are edible/brown crab, lobster and rays/skates *Raja* spp. (SFS, 2013), and in Jersey the most important species are lobster, edible/brown crab and scallops, although spider crab are also important (States of Jersey, 2012).

Weiss *et al.* (2009) suggest that the larvae of edible crab exhibit a particularly narrow range in tolerable temperatures and thus predict that recruitment in this species may be highly vulnerable to the effects of future climate change. By contrast, spider crabs are thought to benefit from warmer seawater temperatures. Early hatching of the spider crab *Maja brachydactyla* on the French Coast adjacent to the

Channel Islands has been related to higher winter-spring sea temperature (Martin and Planque, 2006), and the optimal temperature for spawning and development in this species seems to be around 10–13°C.

4. KNOWLEDGE GAPS AND KEY CHALLENGES

For many years, MCCIP report cards have highlighted a shortage of detailed socio-economic work on UK fishing fleets, and this remains the case in 2016. There have been many recent reports and discussion papers that speculate about impacts (e.g. Cheung *et al.*, 2012; Defra, 2012; Garrett *et al.*, 2015), but very little quantitative analysis focussed on which specific ports and fleet segments could be most impacted. Such quantitative analyses have been carried out elsewhere in the world, for example in the USA and in Australia, where fish and shellfish species have been ranked in terms their overall climate vulnerability (e.g. Hare *et al.*, 2016). Such lists have then been used to determine the most vulnerable fishing communities, based on catch composition and social indicators including employment in the sector, labour force structure and rates of unemployment (e.g. Colburn *et al.*, 2016). Such an exercise has not been carried out for the UK, or indeed anywhere else in Europe, and as a result, adaptation actions that have been devised for the UK fishing industry so far (e.g. Defra, 2012; Garrett *et al.*, 2015) have been somewhat generic. Australian researchers have conducted an analysis of critical elements in the fisheries supply chain under a changing climate (Plagányi *et al.*, 2014). This study identified airports and transport links as key 'pinch points' that need protecting in seafood supply chains; a feature that was also identified by UK stakeholders in the consultation exercise organised by Seafish (see Garrett *et al.*, 2015).

Rather than a shortage of information being the challenge, Garrett *et al.* (2015) has suggested that the main problem to address is that climate change is not necessarily viewed as a priority within the UK fishing industry (underpinning this is a belief that the long-term climate change impacts in the fisheries arena are inherently unknowable, other than at a fairly broad brush level). Investing in more detailed information/evidence may not therefore, be the solution – whereas investing in the structures that support 'sense-making' (i.e. the process by which people give meaning to their direct experience) may be appropriate and useful in the long-term (see Garrett *et al.*, 2015). Climate change is one of the many risks and uncertainties the industry routinely faces. The seafood industry is diverse, complex and dynamic. These characteristics do not lend themselves to centralised approaches. It is inappropriate to consider implementation in terms of a 'grand plan' or programme of adaptation action for the UK seafood industry. Adaptation requires much closer science-industry collaboration and engaged research in the short term, with a move towards a more robust and strategic fisheries knowledge base in the medium term. It is recommended that:

1. Specific adaptation responses are integrated into existing business planning processes of the relevant fishing vessel 'owner' stakeholder.

2. High level surveillance and review of climate change responses is instigated, and repeated on a regular basis, reflecting on the key climate change risks as they affect different parts of the seafood industry (Seafish would be best placed to carry out this role).

Ongoing review of the aggregate climate change impacts on wild capture fisheries at the national level is maintained (e.g. through periodic MCCIP reviews). Impacts of future ocean acidification (OA) on shellfish fisheries (and indirect impacts on finfish fisheries) are still highly uncertain given that responses of species in laboratory experiments have not been uniform, or even consistent. The studies that have attempted to 'scale up' from experimental results to consequences for fisheries (e.g. Cooley and Doney, 2009; Narita and Rehdanz 2016; Fernandes *et al.*, 2017; Pinnegar *et al.*, 2012) have all used crude biological assumptions derived from meta-analyses or individual tank trials, that often have different end-points (e.g. calcification rate, growth trajectory, oxygen consumption) with somewhat spurious links to commercial fisheries. More collaborative work is needed combining empirical and modelling approaches, such as that currently underway in Sweden and Chile exploring whether (or not) OA will affect the taste of cultured shellfish in the future (Dupont *et al.*, 2014).

Fishing operations can be impacted by adverse weather conditions and fishing remains a dangerous occupation. Surprisingly little has been written about the decision-making process whereby fishers decide whether or not to go to sea. The evidence-base is scattered among journals focussing on risk assessment, health and safety, fisheries economics and sociology. Several recently published national or regional assessments of climate change vulnerability have highlighted changes in storminess as a key, if not the primary, long-term concern for this industry, yet the impacts of future storms and adverse weather conditions have not been a major focus of sociological research or scientific investigation. There remains substantial uncertainty and thus low confidence in future projections of storm frequency and intensity over the oceans. Consequently, it is extremely difficult to discern whether fisheries will be more or less likely to be disrupted by poor weather conditions in the future.

5. EMERGING ISSUES (CURRENT AND FUTURE)

Climate change presents challenges to marine species by producing seawater that is warmer, contains less oxygen and is lower in pH than during recent history. To date, most climate-change studies have tended to focus on ecological effects of climate change, including behavioural or physiological acclimation of organisms in response to such pressures; while relatively little is known about the capacity of marine organisms to adapt by evolutionary processes (Waples and Audzijonyti, 2016). A small but growing body of research is, however, starting to focus on evolutionary adaptation; for example Kelly and Hofmann (2013) review current literature on the potential for adaptation to elevated pCO_2 in marine organisms. Important priorities for future research will be to assess adaptation potential to local pH conditions, but also to understand the environmental conditions that commercial species are actually exposed to on a daily basis. Most commercial shellfish live near the coast, where they are exposed to highly variable pH and temperature conditions (Provoost *et al.*, 2010). In some cases, fish or shellfish living in these waters, seasonal (and daily) fluctuations in pH and/or temperatures will be exposed to levels not expected until the late 21st Century elsewhere, thus these species must have some robustness through pre-adaptation.

Reduced oxygen concentrations in marine waters have been cited as a major cause for concern globally (Diaz and Rosenberg, 2008). There is evidence that areas of low oxygen saturation have started to proliferate in the North Sea (Queste *et al.*, 2012). Whether or not these changes are a result of long-term climate change remains unclear, and it is also unknown whether such changes will impact on commercial fish and their fisheries (Townhill *et al.*, 2017). Several authors have highlighted how oxygen concentrations, low pH and elevated temperature interact and determine a species 'scope for growth' (e.g. Pörtner and Knust, 2007). These findings have been used as the basis of models for predicting size and distribution in North East Atlantic fishes, and hence fisheries catch potential (Cheung *et al.*, 2013). Projections of future oxygen concentrations in the North Sea are few and far between, although both van der Molen *et al.* (2013) and Meire *et al.* (2013) suggest that bottom water oxygen concentrations will continue to decrease in the coming decades as a result of long-term climate change.

CITATION

Please cite this document as:

Pinnegar, J. K., Garrett, A., Simpson, S.D., Engelhard, G.H. and van der Kooij, J. (2017) Fisheries. *MCCIP Science Review 2017*, pages XXX, doi:10.14465/2017.arc10.007-fis.

REFERENCES

Agnalt, A.-L., Grefsrud, E.S., Farestveit, E., Larsen, M. and Keulder, F. (2013) Deformities in larvae and juvenile European lobster (*Homarus gammarus*) exposed to lower pH at two different temperatures. Biogeosciences, 10, 7883–7895.

Alheit, J. and Hagen, E. (1997) Long-term climate forcing of European herring and sardine populations. Fisheries Oceanography, 6, 130-139.

Akimova, A., Hufnagl, M., Kreus, M. and Peck, M.A. (2016) Modeling the effects of temperature on the survival and growth of North Sea cod (*Gadus morhua*) through the first year of life. Fisheries Oceanography, 25, 193-209.

Andrew, R. (2014) Cumulative impact of severe weather in Cornwall: Winter 2013 / 2014. November 2014. Cornwall Council. 43pp. www.cornwall.gov.uk/media/10579670/Cornwall-Storm-Impacts-update-19-Nov-2014-V1-3.pdf.

Arnold, K. E., Findlay, H.S., Spicer, J.I., Daniels, C.L., and Boothroyd, D. (2009) Effect of CO_2-related acidification on aspects of the larval development of the European lobster, *Homarus gammarus* (L.). Biogeosciences, 6, 1747–1754, doi:10.5194/bg-6-1747-2009.

Astthorsson, O.S., Valdimarsson, H., Gudmundsdottir, A. and Oskarsson, G.J. (2012) Climate-related variations in the occurrence and distribution of mackerel (*Scomber scombrus*) in Icelandic waters. ICES Journal of Marine Science, 69, 1289–1297.

Baudron, A.R., Needle, C.L., Rijnsdorp, A.D. and Marshall, C.T. (2014) Warming temperatures and smaller body sizes: synchronous changes in growth of North Sea fishes. Global Change Biology, 20, 1023–1031.

Beare D., Burns, F., Peach, K., Portilla, E., Greig, T., McKenzie, E. and Reid, D. (2004) An increase in the abundance of anchovies and sardines in the north-western North Sea since 1995. Global Change Biology, 10, 1–5.

Beggs, S.E., Cardinale, M., Gowen, R.J. and Bartolino, V. (2014) Linking cod (*Gadus morhua*) and climate: investigating variability in Irish Sea cod recruitment. Fisheries Oceanography, 23, 54–64.

Berge, J., Heggland, K., Lønne, O.J., Cottier, F., Hop, H., Gabrielsen, G.W., Nøttestad, L. and Misund, O.A. (2015) First records of Atlantic Mackerel (*Scomber scombrus*) from the Svalbard Archipelago, Norway, with possible explanations for the extension of its distribution. Arctic, 68, 54-61.

Beaugrand, G., Reid, P. C. and Ibańez, F. (2002). Reorganization of North Atlantic marine copepod biodiversity and climate. Science, 296, 1692-1694.

Beaugrand, G., Brander, K.M., Lindley, J.A., Souissi, S. and Reid, P.C. (2003). Plankton effect on cod recruitment in the North Sea. Nature, 426, 661-664.

Blanchard, J.L., Jennings, S., Law, R., Castle, M.D., McCloghrie, P., Rochet, M.-J. and Benoît, E. (2009) How does abundance scale with body size in coupled size-structured food webs? Journal of Animal Ecology, 78, 270–280.

Blanchard, J. L., Jennings, S., Holmes, R., Harle, J., Merino, G., Allen, J. I., Holt, J., Dulvy, N. K. and Barange, M. (2012) Potential consequences of climate change for primary production and fish production in large marine ecosystems. Philosophical Transactions of the Royal Society B: Biological Sciences, 367, 2979–2989.

Booth, L. and Nelson. R. (2014). The perception of chronic and acute risks in the Northern Ireland fishing industry. Safety Science, 68, 41–46.

Brander, K., Neuheimer, A., Andersen, K.H. and Hartvig, M. (2013) Overconfidence in model projections and presenting the uncertainty. ICES Journal of Marine Science, 70, 1065–1068.

Browman, H.I. (2016) Applying organized scepticism to ocean acidification research. ICES Journal of Marine Science, 73, 529–536.

Cheung, W.W.L., Dunne, J., Sarmiento, J.L., and Pauly, D. (2011) Integrating ecophysiology and plankton dynamics into projected maximum fisheries catch potential under climate change in the Northeast Atlantic. ICES Joutrnal of Marine Science, 68, 1008–1018.

Cheung, W.W.L., Pinnegar, J.K., Merino, G., Jones, M.C. and Barange, M. (2012) Review of climate change and marine fisheries in the UK and Ireland. Aquatic Conservation, 22, 368-388.

Cheung, W. W. L., Sarmiento, J. L., Dunne, J., Frölicher, L., Lam, V. W. Y., Palomares, M. L. D., Watson, R. and Pauly, D. (2013) Shrinking of fishes exacerbates impacts of global ocean changes on marine ecosystems. Nature Climate Change, 3, 254-258.

Colburn, L. L., Jepson, M., Weng, C., Seara, T., Weiss, J., Hare, J. A. (2016) Indicators of climate change and social vulnerability in fishing dependent communities along the Eastern and Gulf Coasts of the United States. Marine Policy, 74, 323-333. doi:10.1016/j.marpol.2016.04.030.

Colt, S.G. and Knapp, G.P. (2016) Economic effects of an ocean acidification catastrophe. The American Economic Review, 106, 615-619.

Cook, R.M. and Heath, M.R. (2005) The implications of warming climate for the management of North Sea demersal fisheries. ICES Journal of Marine Science, 62, 1322-1326.

Cooley, S. R. and Doney, S.C. (2009) Anticipating ocean acidification's economic consequences for commercial fisheries. Environmental Research Letters 4 (1 June 2009) 024007.

Cushing, D. (1990) Plankton production and year-class strength in fish populations: an update of the match/mismatch hypothesis. Advances in Marine Biology, 26, 249-293.

Defra (2013) Economics of climate resilience: natural environment – fisheries. February 2013. Department for Environment, Food & Rural Affairs (Defra), UK.

Diaz, R.J. and Rosenberg, R. (2008) Spreading dead zones and consequences for marine ecosystems. Science, 321, 926-929.

Doubleday, Z.A., Prowse, T.A.A., Arkhipkin, A., Pierce, G.J., Semmens, J., Steer, M., Leporati, S.C., Lourenço, S., Quetglas, A., Sauer, W. and Gillanders, B. M. (2016) Global proliferation of cephalopods. Current Biology, 26, R406–R407.

Drinkwater, K. F. (2005) The response of Atlantic cod (*Gadus morhua*) to future climate change. ICES Journal of Marine Science, 62, 1327-1337.

Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmüller, V., Dye, S.R. and Skjoldal, H.R. (2008) Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. Journal of Applied Ecology, 45, 1029–1039.

Dupont, S., Hall, E. and Lundve, B. (2014) First evidence of altered sensory quality in a shellfish exposed to decreased pH relevant to ocean acidification. Journal of Shellfish Research, 33, 857-861.

Engelhard, G.H., Pinnegar, J.K., Kell, L.T. and Rijnsdorp, A.D. (2011) Nine decades of North Sea sole and plaice distribution. ICES Journal of Marine Science, 68, 1090–1104.

Engelhard, G.H., Righton, D.A. and Pinnegar, J.K. (2014) Climate change and fishing: a century of shifting distribution in North Sea cod. Global Change Biology, 20, 2473-2483. doi:10.1111/gcb.12513

Fernandes, J.A., Papathanasopoulou, E., Hattam, C., Queirós, A.M., Cheung, W.W.L., Yool, A., Pope, E.C., Flynn, K.J., Merino, G., Calosi, P., Beumont, N., Austen, M.C., Widdicombe, S. and Barange, M. (2017) Estimating the ecological, economic and social impacts of ocean acidification and warming on UK fisheries. Fish and Fisheries, 18, 389-444.

Fincham, J. I., Rijnsdorp, A. D. and Engelhard, G. H. (2013) Shifts in the timing of spawning in sole linked to warming sea temperatures. Journal of Sea Research, 75, 69-76.

Fox, C.J., Planque, B.P. and Darby, C.D. (2000) Synchrony in the recruitment time-series of plaice (*Pleuronectes platessa* L) around the United Kingdom and the influence of sea temperature. Journal of Sea Research, 44, 159−168.

Freitas, C., Olsen, E.M., Moland, E., Ciannelli, L. and Knutsen, H. (2015) Behavioral responses of Atlantic cod to sea temperature Changes. Ecology and Evolution, 5, 2070–2083.

Garrett, A., Buckley, P. and Brown, S. (2015) Understanding and responding to climate change in the UK seafood industry: Climate change risk adaptation for wild capture seafood. A Seafish report to the UK Government under the Climate Change Adaptation Reporting Power. Seafish, Edinburgh, 104 pp.

Genner, M.J., Halliday, N.C., Simpson, S.D., Southward, A. J., Hawkins, S.J. and Sims, D.W. (2010) Temperature-driven phenological changes within a marine larval fish assemblage. Journal of Plankton Research, 32, 699-708.

Goikoetxea, N. and Irigoien, X. (2013) Links between the recruitment success of northern European hake (*Merluccius merluccius* L.) and a regime shift on the NE Atlantic continental shelf. Fisheries Oceanography, 22, 459-476.

Greve, W., Prinage, W.S., Zidowitz, H., Nast, J. and Reiners, F. (2005) On the phenology of North Sea ichthyoplankton. ICES Journal of Marine Science, 62, 1216-1223

Gröger, J.P., Kruse, G.H. and Rohlf, N. (2010) Slave to the rhythm: how large-scale climate cycles trigger herring (*Clupea harengus*) regeneration in the North Sea. ICES Journal of Marine Science, 67. 454–465.

Hannesson, R. (2013) Sharing the Northeast Atlantic mackerel. ICES Journal of Marine Science, 70, 259–269.

Hare, J.A., Morrison, W.E., Nelson, M.W., Stachura, M. M., Teeters, E.J., Griffis, R.B., *et al.* (2016) A vulnerability assessment of fish and invertebrates to climate change on the Northeast U.S. Continental Shelf. PLoS ONE 11(2): e0146756. doi:10.1371/journal.pone.0146756

Hastie, L., Pierce, G., Pita, C., Viana, M., Smith, J. and Wangvoralak, S. (2009) Squid fishing in UK waters. A Report to SEAFISH Industry Authority. School of Biological Sciences, University of Aberdeen.

Hátún, H. and Payne, M.R. (2014) Report reviewing the current state-of-the-art of North Atlantic marine ecosystem predictability. NACLIM Deliverable D41.11. 30 April 2014. 50 pp.

Hazeleger, W., Wouters, B., van Oldenborgh, G. J., Corti, S., Palmer, T., Smith, D., Dunstone, N., Kröger, J., Pohlmann, H. and von Storch, J.-S. (2013) Predicting multiyear North Atlantic Ocean variability. Journal of Geophysical Research – Oceans, 118, 1087-1098.

Heath, M. R. (2007) Responses of fish to climate fluctuations in the Northeast Atlantic. In: Emery, L. E. (ed.) The Practicalities of Climate Change: Adaptation and Mitigation. Proceedings of the 24th Conference of the Institute of Ecology and Environmental Management, Cardiff.

Hiddink, J.G. and ter Hofstede, R. (2008) Climate induced increases in species richness of marine fishes. Global Change Biology, 14, 453-460.

Hilmi, N., Allemand, D., Cinar, M., Cooley, S., Hall-Spencer, J.M., Haraldsson, G., Hattam, C., Jeffree, R.A., Orr, J.C., Rehdanz, K., Reynaud, S., Safa, A. and Dupont, S. (2014) Exposure of Mediterranean countries to ocean acidification. Water, 6, 1719-1744. doi:10.3390/w6061719.

Hughes, K.M., Dransfeld, L. and Johnson, M.P. (2014) Changes in the spatial distribution of spawning activity by north-east Atlantic mackerel in warming seas: 1977–2010. Marine Biology, 161, 2563–2576.

Hughes, K.M., Dransfeld, L. and Johnson, M.P. (2015) Climate and stock influences on the spread and locations of catches in the northeast Atlantic mackerel fishery. Fisheries Oceanography, 24, 540–552.

ICES (2013a) Report of the Ad Hoc Group on the Distribution and Migration of Northeast Atlantic Mackerel (AGDMM), 30-31 August 2011 and 29-31 May 2012, ICES Headquarters, Copenhagen. ICES CM 2013/ACOM:58. 211pp.

ICES (2013b). Interim Report of the Working Group on Integrated Ecosystem Assessments for the Norwegian Sea (WGINOR), 19–23August 2013, Bergen, Norway. ICES Document CM 2013/ SSGRSP: 07. 94 pp.

ICES (2015a) 5.3.43 - Sea bass (*Dicentrarchus labrax*) in Divisions IVb and c, VIIa, and VIId–h (Central and South North Sea, Irish Sea, English Channel, Bristol Channel, Celtic Sea). ICES Advice on fishing opportunities, catch, and effort Celtic Seas and Greater North Sea Ecoregions. ICES Advice 2015, Book 5, 30 June 2015.

ICES (2015b) 6.3.4 - Cod (*Gadus morhua*) in Subarea IV and Divisions VIId and IIIa West (North Sea, Eastern English Channel, Skagerrak). ICES Advice on fishing opportunities, catch, and effort Greater North Sea and Celtic Seas Ecoregions. ICES Advice 2015, Book 6. 30 June 2015.

ICES IROC (2014) ICES Report on Ocean Climate 2014. In: Larsen, K. M. H., Gonzalez-Pola, C., Fratantoni, P., Beszczynska-Moller, A. and Hughes, S. L. (Eds.). ICES Cooperative Research Report No. 329. 139 pp.

IPCC (2013) Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change. Stocker, T. F., Qin, D., Plattner, G.-K., Tignor, M., Allen, S. K., Boschung, J., Nauels, A., Xia, Y., Bex, V., Midgley, P. M. (eds.).

Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. 1535 pp.

Jones, M.C., Dye, S.R., Pinnegar, J.K., Warren, R. and Cheung, W.W.L. (2015) Using scenarios to project the changing profitability of fisheries under climate change. Fish and Fisheries, 16, 603-622.

Karpechko, A.Y. (2010) Uncertainties in future climate attributable to uncertainties in future Northern Annular Mode trend. Geophysical Research Letters, 37, L20702. doi: 10.1029/2010gl044717.

Kell, L.T., Pilling, G.M. and O'Brien, C.M. (2005) Implications of climate change for the management of North Sea cod (*Gadus morhua*). ICES Journal of Marine Science, 62, 1483-1491.

Kelly, M.W. and Hofmann, G.E. (2013) Adaptation and the physiology of ocean acidification. Functional Ecology, 27, 980–990.

Kempf, A., Stelzenmüller, V., Akimova, A. and Floeter, J. (2013) Spatial assessment of predator–prey relationships in the North Sea: the influence of abiotic habitat properties on the spatial overlap between 0-group cod and grey gurnard. Fisheries Oceanography, 22, 174–192.

Koenigstein, S., Mark, F.C., Gößling-Reisermann, S., Reuter, H. and Pörtner, H.-O. (2016) Modelling climate change impacts on marine fish populations: process-based integration of ocean warming, acidification and other environmental drivers. Fish and Fisheries, 17, 972-1004.

Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M. and Gattuso, J.P. (2013). Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Global Change Biology, 19, 1884–1896.

Lynam, C.P., Cusack, C. and Stokes, D. (2010) A methodology for community-level hypothesis testing applied to detect trends in phytoplankton and fish communities in Irish waters. Estuarine, Coastal and Shelf Science, 87, 451-462.

MacKenzie, B.R., Payne, M.R., Boje, J., Høyer, J.L. and Siegstad, H. (2014a) A cascade of warming impacts brings bluefin tuna to Greenland waters. Global Change Biology, 20, 2484–2491.

Mackenzie, C.L., Ormondroyd, G.A., Curling, S.F., Ball, R.J., Whiteley, N.M. and Malham, S.K. (2014b) Ocean warming, more than acidification, reduces shell strength in a commercial shellfish species during food limitation. PLoS ONE, 9(1), e86764. doi:10.1371/journal.pone.0086764

Martin, J. and Planque, B. (2006) Variability in the onset of hatching of *Maja brachydactyla* Balss, 1922 (Brachyura: Majidae) in the English Channel in relation to sea temperature. Invertebrate Reproduction and Development, 49, 143-150.

Masselink, G., Scott, T., Poate, T., Russell, P., Davidson, M. and Conley, D. (2016) The extreme 2013/2014 winter storms: hydrodynamic forcing and coastal response along the southwest coast of England. Earth Surface Processes and Landforms, 41, 378-391.

Matei, D., Pohlmann, H., Jungclaus, J., Müller, W., Haak, H. and Marotzke, J. (2012) Two tales of initializing decadal climate prediction experiments with the ECHAM5/MPI-OM model. Journal of Climate, 25, 8502-8523.

Matthews ,T,. Murphy, C., Wilby, R.L. and Harrigan, S. (2014) Stormiest winter on record for Ireland and UK. Nature Climate Change, 4, 738-740.

Meire, L., Soetaert, K.E.R. and Meysman, F.J.R. (2013) Impact of global change on coastal oxygen dynamics and risk of hypoxia. Biogeosciences, 10, 2633-2653.

MMEA (2013) Manx Marine Environmental Assessment - Commercial Fisheries & Sea Angling. October 2013. Isle of Man Government, 70 pp.

MMO (2015) UK Sea Fisheries Statistics 2014. Marine Management Organisation (MMO), Newcastle upon Tyne, UK. 156 pp.

Montero-Serra, I., Edwards, M. and Genner, M.J. (2015) Warming shelf seas drive the subtropicalization of European pelagic fish communities. Global Change Biology, 21, 144–153.

Morel, G., Amalberti, R. and Chauvin, C. (2008) Articulating the differences between safety and resilience: the decision-making process of professional sea-fishing skippers. Human Factors, 50, 1–16.

Narita, D. and Rehdanz, K. (2017) Economic impact of ocean acidification on shellfish production in Europe, Journal of Environmental Planning and Management, 60, 500-518. doi: 10.1080/09640568.2016.1162705.

Neumann, H., de Boois, I., Kröncke, I. and Reiss, H. (2013) Climate change facilitated range expansion of the non-native angular crab *Goneplax rhomboides* into the North Sea. Marine Ecology-Progress Series, 484, 143-153.

Nicolas, D., Rochette, S., Llope, M. and Licandro, P. (2014) Spatio-temporal variability of the North Sea cod recruitment in relation to temperature and zooplankton. PLoS ONE, 9(2), e88447. doi:10.1371/journal.pone.0088447.

Olafsdottir, A.H., Slotte, A., Jacobsen, J.A., Oskarsson, G.J., Utne, K.R., and Nøttestad, L. (2016) Changes in weight-at-length and size-at-age of mature Northeast Atlantic mackerel (*Scomber scombrus*) from 1984 to 2013: effects of mackerel stock size and herring (*Clupea harengus*) stock size. – ICES Journal of Marine Science, 73: 1255–1265.

Ostle, C., Williamson, P., Artioli, Y., Bakker, D.C.E., Birchenough, S., Davis, C.E., Dye, S., Edwards, M., Findlay, H.S., Greenwood, N., Hartman, S., Humphreys, M. P., Jickells, T., Johnson, M., Landschützer, P., Parker, R., Pearce, D., Pinnegar, J., Robinson, C., Schuster, U., Silburn, B., Thomas, R., Wakelin, S., Walsham P. and Watson, A.J. (2016) Carbon dioxide and ocean acidification observations in UK waters: Synthesis report with a focus from 2010 - 2015. UK Ocean Acidification Research Programme (UKOA). doi: 10.13140/RG.2.1.4819.4164.

O'Sullivan, D., Lordan, C., Doyle, J., Berry, A. and Lyons, K. (2015) Metapopulation connectivity via larval transport ofthe Norway lobster *Nephrops norvegicus* in waters around Ireland: a modelled approach. Marine Ecology-Progress Series, 534, 95-106.

Ottersen, G., Stige, L.C., Durant, J.M., Chan, K.S., Rouyer, T. A., Drinkwater, K.F., Stenseth, N.C.(2013) Temporal shifts in recruitment dynamics of North Atlantic fish stocks: effects of spawning stock and temperature. Marine Ecology-Progress Series, 480, 205-225.

Pawson, M.G., Kupschus, S. and Pickett, G.D. (2007) The status of sea bass (*Dicentrarchus labrax*) stocks around England and Wales, derived using a separable catch-at-age model, and implications for fisheries management. ICES Journal of Marine Science, 64, 346–356.

Payne, M.R., Egan, A., Fässler, S.M.M., Hátún, H., Holst, J. C., Jacobsen, J.A., Slotte, A. and Loeng, H. (2012) The rise and fall of the NE Atlantic blue whiting (*Micromesistius poutassou*). Marine Biology Research, 8, 475–487.

Pécuchet, L., Nielsen, J.R. and Christensen, A. (2015) Impacts of the local environment on recruitment: a comparative study of North Sea and Baltic Sea fish stocks. ICES Journal of Marine Science, 72, 1323–1335.

Perry, A.L., Low, P.J., Ellis, J.R. and Reynolds, J.D. (2005) Climate change and distribution shifts in marine fishes. Science, 308, 1912–1915.

Petitgas, P., Alheit, J., Peck, M.A., Raab, K., Irigoien, X., Huret, M., van der Kooij, J., Pohlmann, T., Wagner, C., Zarraonaindia, I. and Dickey-Collas, M. (2012) Anchovy population expansion in the North Sea. Marine Ecology-Progress Series, 444, 1-13.

Petitgas, P., Rijnsdorp, A.D., Dickey-Collas, M. Engelhard, G.H., Peck, M.A., Pinnegar, J.K., Drinkwater, K. Huret, M. and Nash R.D.M. (2013) Impacts of climate change on the complex life cycles of fish. Fisheries Oceanography, 22, 121-139.

Pinnegar, J. (2006) Impacts of climate change on fisheries. Marine Climate Change Impacts Partnership (MCCIP), 10pp.

Pinnegar, J., Watt, T., and Kennedy, K. (2012) CCRA Risk Assessment for the Marine and Fisheries Sector. UK 2012 Climate Change Risk Assessment, Defra, London.

Pinsky, M.L., Worm, B., Fogarty, M.J., Sarmiento, J.L. and Levin, S.A. (2013) Marine taxa track local climate velocities. Science, 341, 1239-1242.

Pitois, S.G., Jansen, T. and Pinnegar, J. (2015) The impact of environmental variability on Atlantic mackerel *Scomber scombrus* larval abundance to the west of the British Isles. Continental Shelf Research, 99, 26-34.

Pitois, S.G., Lynam, C.P., Jansen,T., Halliday, N. and Edwards, M. (2012) Bottom-up effects of climate on fish populations: data from the continuous plankton recorder. Marine Ecology-Progress Series, 456, 169–186.

Plagányi, É.E., van Putten, I., Thébaud, O., Hobday, A.J., Innes, J., *et al.* (2014) A quantitative metric to identify critical elements within seafood supply networks. PLoS ONE 9(3), e91833. doi:10.1371/journal.pone.0091833.

Pörtner, H.O. and Farrell, A.P. (2008) Physiology and climate change. Science, 322, 690-692.

Pörtner, H.O. and Knust, R. (2007) Climate change affects marine fishes through the oxygen limitation of thermal tolerance. Science, 315, 95-97.

Provoost, P., van Heuven, S., Soetaert, K., Laane, R.W.P.M. and Middelburg, J.J. (2010) Seasonal and long-term changes in pH in the Dutch coastal zone. Biogeosciences, 7, 3869–3878.

van der Molen, J., Aldridge, J.N., Coughlan, C., Parker, E.R., Stephens, D. and Ruardij, P. (2013) Modelling marine ecosystem response to climate change and trawling in the North Sea. Biogeochemistry, 113, 213-236.

van Leewen, S.M., Le Quesne, W.F. and Parker, E.R. (2016) Potential future fisheries yields in shelf waters: a model study of the effects of climate change and ocean acidification. Biogeosciences, 13, 441–454.

Waples, R.S. and Audzijonyte, A. (2016) Fishery-induced evolution provides insights into adaptive responses of marine species to climate change. Frontiers in Ecology and the

Queste, B.Y., Fernand, L., Jickells, T.D. and Heywood, K. J. (2012) Spatial extent and historical context of North Sea oxygen depletion in August 2010. Biogeochemistry, 113, 53-68.

Raab, K., Llope, M., Nagelkerke, L.A.J., Rijnsdorp, A.D., Teal, L.R., Licandro, P., Ruardij, P., and Dickey-Collas, M. (2013) Influence of temperature and food availability on juvenile European anchovy *Engraulis encrasicolus* at its northern boundary. Marine Ecology-Progress Series, 488, 233-245.

Rijnsdorp, A.D., Peck, M.A., Engelhard, G.H., Möllmann, C., and Pinnegar, J.K. (2009) Resolving the effect of climate change on fish populations. ICES Journal of Marine Science, 66, 1570-1583.

Royal Society (2005) Ocean acidification due to increasing atmospheric carbon dioxide. Report, June 2005. 68 pp.

Rutterford, L.A., Simpson, S.D., Jennings, S., Johnson, M.P., Blanchard, J.L., Schön, P.-J., Sims, D.W., Tinker, J.Y. and Genner, M.J. (2015) Future fish distributions constrained by depth in warming seas. Nature Climate Change 5, 569-573.

Sanders, M.B., Bean, T.P., Hutchinson, T.H., Le Quesne, W.J.F. (2013) Juvenile king scallop, *Pecten maximus*, is potentially tolerant to low levels of ocean acidification when food is unrestricted. PLoS ONE, 8(9), e74118. doi: 10.1371/journal.pone.0074118.

SFS (2013) Sea Fisheries Section - Annual Report 2013. St. Martin, Guernsey, 17 pp.

Simpson, S. D., Jennings, S., Johnson, M. P., Blanchard, J. L., Schön, P.-J., Sims, D. W. and Genner, M. J. (2011) Continental shelf-wide response of a fish assemblage to rapid warming of the sea. Current Biology, 21, 1565–1570.

Small, D. P., Calosi, P., Boothroyd, D., Widdicombe, S. and Spicer, J. I. (2015) Stage-specific changes in physiological and life-history responses to elevated temperature and pCO_2 during the larval development of the European lobster *Homarus gammarus* (L.). Physiological and Biochemical Zoology, 88, 494-507.

Smith, D.M., Cusack, S., Colman, A.W., Folland, C.K., Harris, G.R. and Murphy, J.M.(2007) Improved surface temperature prediction for the coming decade from a global climate model. Science, 317, 796-799.

Smith, D.M., Eade, R. and Pohlmann, H. (2013) A comparison of full-field and anomaly initialization for seasonal to decadal climate prediction. Climate Dynamics, 41, 3325-3338.

States of Jersey (2012) Jersey in Figures, 2012. States of Jersey Statistics Unit, St Helier, Jersey, Channel Islands. 104 pp.

Styf, H.K., Nilsson Sköld, H. and Eriksson, S.P. (2013) Embryonic response to long-term exposure of the marine crustacean *Nephrops norvegicus* to ocean acidification and elevated temperature. Ecology and Evolution, 3, 5055–5065.

Townhill, B.L., Pinnegar, J.K., Righton, D.A. and Metcalfe, J.D. (2017) Fisheries, low oxygen and climate change: how much do we really know? Journal of Fish Biology, 90, 3, 723-750. doi: 10.1111/jfb.13203.

van der Kooij, J., Fassler, S.M.M., Stephens, D., Readdy, L., Scott, B.E., and Roel, B.A. (2016) Opportunistically recorded acoustic data support Northeast Atlantic mackerel expansion theory. – ICES Journal of Marine Science 73, 1115–1126.

van der Kooij, J., Engelhard, G.H. and Righton, D. (2016) Climate change and squid range expansion in the North Sea. Journal of Biogeography, 43, 11, 2285-2298. doi: 10.1111/jbi.12847.

van der Molen, J., Aldridge, J.N., Coughlan, C., Parker, E.R., Stephens, D. and Ruardij, P. (2013) Modelling marine ecosystem response to climate change and trawling in the North Sea. Biogeochemistry, 113, 213-236.

van Leewen, S.M., Le Quesne, W.F. and Parker, E.R. (2016) Potential future fisheries yields in shelf waters: a model study of the effects of climate change and ocean acidification. Biogeosciences, 13, 441–454.

Waples, R.S. and Audzijonyte, A. (2016) Fishery-induced evolution provides insights into adaptive responses of marine species to climate change. Frontiers in Ecology and the Environment, 14, 217–224

Weiss, M., Thatje, S., Heilmayer, O., Anger, K. and Brey, T. (2009) Influence of temperature on the larval development of the edible crab, *Cancer pagurus*. Journal of the Marine Biological Association of the UK, 89, 753-759.

Wood, H.L., Eriksson, S.P., Nordborg, M. and Styf, H.K. (2015) The effect of environmental stressors on the early development of the Norway lobster *Nephrops norvegicus*. Journal of Experimental Marine Biology and Ecology, 473, 35–42.

Woodhead, P.M.J. (1964) The death of North Sea fish during the winter of 1962/63, particularly with reference to the sole, *Solea vulgaris*. Helgoländer Wissenschaftlichen Meeresuntersuchungen, 10, 283-300.

Xavier, J.C., Peck, L.S., Fretwell, P. and Turner, J. (2016) Climate change and polar range expansions: could cuttlefish cross the Arctic? Marine Biology, 163. doi: 10.1007/s00227-016-2850-x.