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Future of the Sea: Biological Responses to Ocean Warming

Foresight – Future of the Sea Evidence Review

Foresight, Government Office for Science

Biological Responses to Ocean Warming

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Contents

Executive Summary

Global sea surface temperatures have risen by 0.7°C from pre-industrial times (1870–1899) to the recent past (2005–2014). This trend is projected to continue, with a rise of between 1.2°C and 3.2°C by 2100, depending on greenhouse gas emission levels. This Evidence Review examines how warming seas have already influenced marine organisms, and considers future implications of projected warming for capture fisheries, aquaculture and biodiversity conservation in the UK and the British Overseas Territories (BOT).

We have high confidence that warming has strongly affected marine biodiversity and commercial fisheries over the last 50 years. Although there are considerable gaps in our knowledge, particularly with regard to our ability to reliably predict future changes, *the implementation of steps to mitigate and adapt to future warming will reduce long-term impacts.*

Key findings are below.

- *Studies of marine biological responses to past environmental changes show an overwhelming pattern of change consistent with warming.* Warming-induced trends include poleward shifts in species distributions, advancements of the breeding seasons, and increased abundance of warm water species while cold water species decline.
- *Although future shifts in species composition appear likely, the implications of warming seas for the UK fish production and the fishing industry are unclear, as the issue has not been researched in comprehensive detail.* Warming seas have contributed to long-term declines in cold water species, for example Atlantic cod. However an increase in warm water species, for example red mullet, could bring new catch potential to UK waters. UK capture fisheries and landings by commercial vessels have been affected by ocean warming, but predictive modelling approaches that incorporate climate and fishing as drivers of change are required to more accurately predict future changes in fish stocks, and the impact of these on commercial fisheries.
- UK aquaculture is highly dependent on two core species, the Atlantic salmon and blue mussel, both of which are close to southern limit of their European range, and

therefore vulnerable to warming. *There are concerns that warming seas will lead to thermal stress, lower growth, reduced food conversion efficiency, and a higher incidence of economically significant parasites and pathogens.*

- Species and habitats of high conservation importance within marine reserves in the UK and BOT are threatened by warming seas. The UK has an international obligation to continue monitoring biodiversity within territorial waters and there are concerns that the present network of Marine Protected Areas may need to be revised if warming seas affect the distribution of threatened biodiversity.
- Coral reef habitats in the Indo-Pacific overseas territories are projected to suffer annual warming-induced bleaching events *that may lead to substantial economic impact for Indo-Pacific fisheries.*
- *There is a high risk that warming seas will facilitate the invasion of UK waters by invasive species with proven negative effects on capture fisheries and aquaculture.* Predictions of future impacts of warming will need to account for the effects of extreme temperature events on marine organisms, as well as interactions with other stressors including ocean acidification, fisheries and invasive species.
- Recent work has suggested a weakening of the Atlantic meridional overturning circulation (AMOC), the current that transports warmer water northwards through the Atlantic. However, it is uncertain if this represents multidecadal variability or is part of a long-term trend. Modelling of long-term projections has suggested that global warming may lead to further weakening of the AMOC over the next century, and associated cooling of the North Atlantic waters.

1. Evidence of Environmental Change

1.1 Changing Sea Temperatures

Sea surface temperature records collected using ships and buoys from 1870 onwards have been compiled and bias-corrected by the UK Met Office into the Hadley Centre Global Sea Ice and Sea Surface Temperature (HadISST) dataset (Rayner et al. 2003). These data are available as interpolated monthly averages over 1° latitude and 1° longitude grid squares. The records demonstrate that average global sea surface temperature has risen by 0.72°C between pre-industrial times (1870–1899) and recent years (2005–2014) (Gattuso et al. 2015). Importantly, sea temperature change has not been spatially consistent over a global scale. Relatively low rises of sea surface temperatures of 0.2°C and 0.4°C have taken place in South Georgia and the Falkland Islands respectively (Figure 1), while there have been more striking changes in sea temperatures in other locations. In UK waters, mean annual sea temperatures have risen by 0.8°C since 1870, and have shown a consistent warming trend from the 1970s onwards (Figure 1). The waters surrounding the Chagos archipelago have risen by ~0.7°C, while the Pitcairn Islands have seen a rise of 0.4°C.

Future projections of sea surface temperature are available from Coupled Model Intercomparison Project Phase 5 (CMIP5) General Circulation Models (GCMs). These were developed for the Intergovernmental Panel on Climate Change Fifth Assessment Report (IPCC 2014), and project alternative futures for the 21st century under scenarios of varying severity. Each scenario is a Representative Concentration Pathway (RCP), with the RCP numbers referring to radiative forcing projected, given alternative greenhouse gas concentration trajectories (Harris et al. 2014). RCP2.6 assumes high technological development, and a levelling off of greenhouse emissions by 2050, followed by a return to 2020 levels by 2100. This pathway predicts a rise in global sea surface temperature of 0.8°C by 2050, and 1.2°C by 2100, relative to 1870–1899 temperatures. RCP8.5 assumes low technological development and a continued high level of greenhouse gas emissions. This pathway predicts a rise in global sea surface temperature of 1.5°C by 2050, and 3.2°C by 2100, relative to 1870–1899 temperatures (Figure 1).

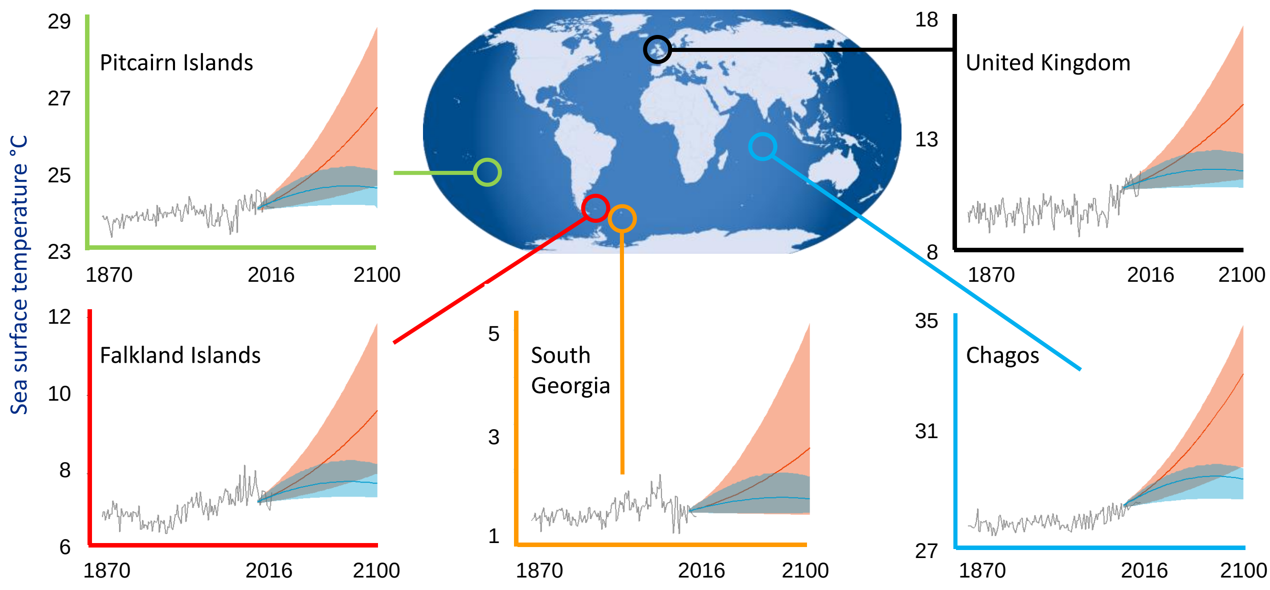

Figure 1. Hadley Centre Global Sea Ice and Sea Surface Temperature: observed (1870–2014) and projected Representative Concentration Pathway (RCP) model (2000–2100) sea surface temperatures in UK waters and British Overseas Territories

Projected temperatures are biannual averages for RCP 2.6 (blue) and RCP 8.5 (red) climate scenarios, and shaded areas show the 5th and 95th percentiles from the projections of 10 climate models; observed data are shown in greater detail in the Appendix

1.2 Environmental Variables that Vary with Temperature

- **Sea ice.** Mean annual Arctic sea-ice extent has declined from 12.5 million km^2 in 1979 to 11 million km^2 in 2013 (Simmonds 2015). This decline is predicted to continue towards 2050 (Stroeve et al. 2012), and has been attributed to global warming. Mean annual Antarctic sea-ice extent has increased from 12.1 million km^2 in 1979 to 12.9 million km^2 in 2013 (Simmonds 2015). Antarctic sea-ice expansion has been attributed to enhanced freshwater input from melting continental ice shelves that serve to insulate sea ice from deeper warm waters (Bintanja et al. 2013).
- **Ocean currents.** Movement of water masses is determined by ocean temperature, atmospheric wind forcing and freshwater input, all of which are vulnerable to global warming. Recent work has suggested a weakening of the Atlantic meridional overturning circulation (AMOC), the current that transports warmer water northwards through the Atlantic (in 2008–2012 relative to 2004–2008; Smeed et al. 2014). However, it is uncertain if this represents multidecadal variability or is part of

a long-term trend. Modelling of long-term projections has suggested that global warming may lead to further weakening of the AMOC over the next century, and associated cooling of the North Atlantic waters (Bakker et al. 2016; Liu et al. 2017).

- **Dissolved oxygen**. Warmer waters carry less dissolved oxygen, thus temperature can affect the growth and survivorship of fish due to low oxygen availability (Pörtner and Knust 2007). Warming can also reduce oxygen solubility and increase the strength and duration of stratification between the water layers (Townhill et al. 2016). This leads to a reduction in oxygen flow from the upper to lower water columns, and can exacerbate eutrophication-driven low-oxygen (hypoxic) dead zones in coastal waters (Rabalais et al. 2009).
- **Ocean acidity.** Sea temperature co-varies with ocean pH on a global scale, as both are dependent on the concentration of CO_2 in the atmosphere. Typically these are studied as separate drivers of change in marine biological communities, in part because they often decoupled over narrower spatial and temporal scales. Nevertheless, they can act simultaneously and synergistically on marine organisms, affecting growth and development (Kroeker et al. 2013).
- **Sea level.** Sea level rises take place due to thermal expansion of oceanic waters and deglaciation. It has been estimated that sea levels have risen by 25 cm over the last 200 years (Jevrejeva et al. 2008). Median global rises of 48 cm and 64 cm by 2090 are projected for the RCP4.5 and RCP8.5 scenarios, relative to the 1986–2005 baseline, albeit with considerable uncertainty and spatial variation (Jackson and Jevrejeva 2016).

2. Evidence of Ocean-Warming Impacts on Marine Life

2.1 Introduction

Physiological processes of plants and animals are highly dependent on temperature, and shifts in environmental temperatures strongly affect the performance of species (Pörtner and Farrell 2008). The nature of the performance response depends on the thermal tolerance of the individual, which is dependent on adaptation (over evolutionary time) and acclimation (over the lifespan of the individual) (Somero 2010).

Abundance of species can be strongly linked to warming through multiple ecological mechanisms. In established local populations, warming can directly facilitate enhanced reproduction, settlement or growth by providing more optimal physiological conditions (Parmesan, 2006). However excessive warming can also reduce species abundance by directly negatively affecting these physiological processes, and thus reducing survivorship and growth (e.g. Neuheimer et al. 2011). Warming can facilitate immigration and the survivorship of immigrants, by providing new opportunities to colonise a habitat that was previously too cold to operate within (Parmesan and Yohe 2003; Wernberg et al. 2016). It can also lead to loss of species from waters that become too warm, either due to death or migration of adults, or failed recruitment of individuals (Wernberg et al. 2016).

Warming can increase abundance indirectly, by improving prey abundance, or reducing the abundance of natural enemies, such as predators, prey or pathogens (Hughes 2000). However it can also lead to population declines, by the loss of important prey or symbiont species. Corals in particular are highly dependent on their algal symbionts (zooxanthellae) that provide key nutrients, but thermal stress results in the expulsion of the symbionts, resulting in coral bleaching, and gradual coral starvation (Hoegh-Guldberg 1999).

Biological responses to temperature changes are well known from laboratory trials, but the strongest evidence of responses to global-scale ocean warming comes from field studies conducted over multiple years, either as sustained time series, or ‘then and now’ comparisons (Mieszkowska et al. 2014). It is possible to group responses as relating to abundance (i.e. a change in numbers of the population), phenology (a change in the timing of life history events), distribution (a change to geographic area covered by the species) or demography (a change in average survivorship, or average growth), or calcification (precipitation of calcium carbonate in skeletal tissue). Typically, abundance increases are most commonly observed at the leading (poleward) edge of species distributions, while abundance declines are most commonly observed at trailing edges of species distributions, as species become directly vulnerable to excessively high temperatures (Poloczanka et al. 2013). In the marine environment, there is strong evidence of warming leading to poleward shifts in distributions, advancement in the timing of migration and spawning, and increases in the abundance of ‘warm water’ species (that favour warmer environments than the one currently under consideration) (Poloczanka et al. 2013).

2.2 Literature Review of Warming-Related Biological Changes in the Marine Environment

We obtained records of biological responses to warming from a database of quantitative research published between 1991 and 2012 that formed the basis of a recent review by Poloczanka et al. (2013). We retained data that looked at responses to temperature, at the levels of species or genera (hereinafter referred to as 'species'). These data were augmented with further records published 2012–2016. Following the method published by Poloczanka et al. (2013) we required all studies to cover a time span of 19 years, and to include recent warming (1990 onwards). Species-level responses were retained if they related to abundance, phenology, distribution, demography or calcification. These responses were then determined to be consistent or opposite relative to expectations of warming, or if they described a pattern of 'no change'. Whether trends were consistent with warming, or otherwise, was based on the expert opinions of the authors, on the basis of the known geographic range and/or thermal occupancy patterns of species in relation to the location of study. For example, populations at the leading (poleward) edge of species distributions would be expected to show enhanced responses in measured variables, while populations at trailing (equatorward) edges of species distributions would be expected to have diminished responses in measured variables.

In total, 1774 species-level responses were recorded in the dataset, across 196 papers. Of these 1101 were consistent with expectations from ocean warming, 404 showed no change, and 271 were not consistent with ocean warming.

Long-term studies from the marine environment show strong evidence of population-level responses driven by ocean warming. Within five classes of biological responses, the majority of quantified biological responses were consistent with those expected from warming (Figure 2). In all individual species groups, more species were showing changes consistent with warming than were showing no change, or inconsistent responses (Figure 3).

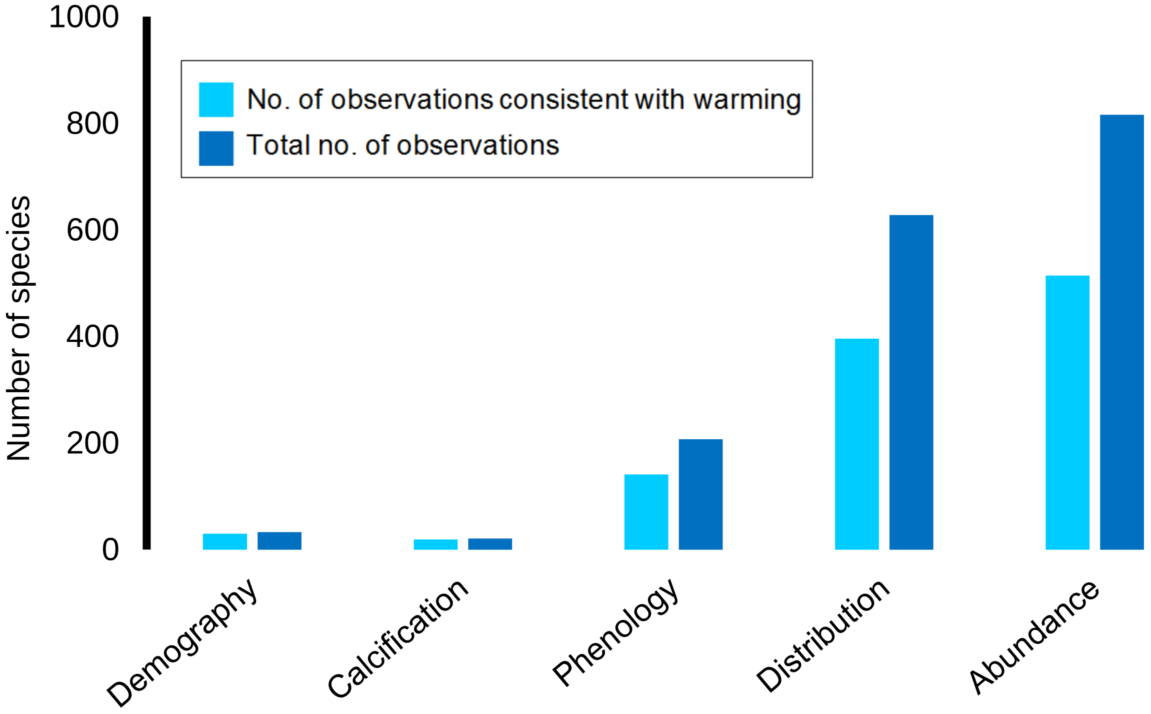

Figure 2. The proportion of species-level biological responses reported in the literature that are consistent with expectations from ocean warming, across 196 peer review papers; other species showed either no change, or a change inconsistent with the pattern expected

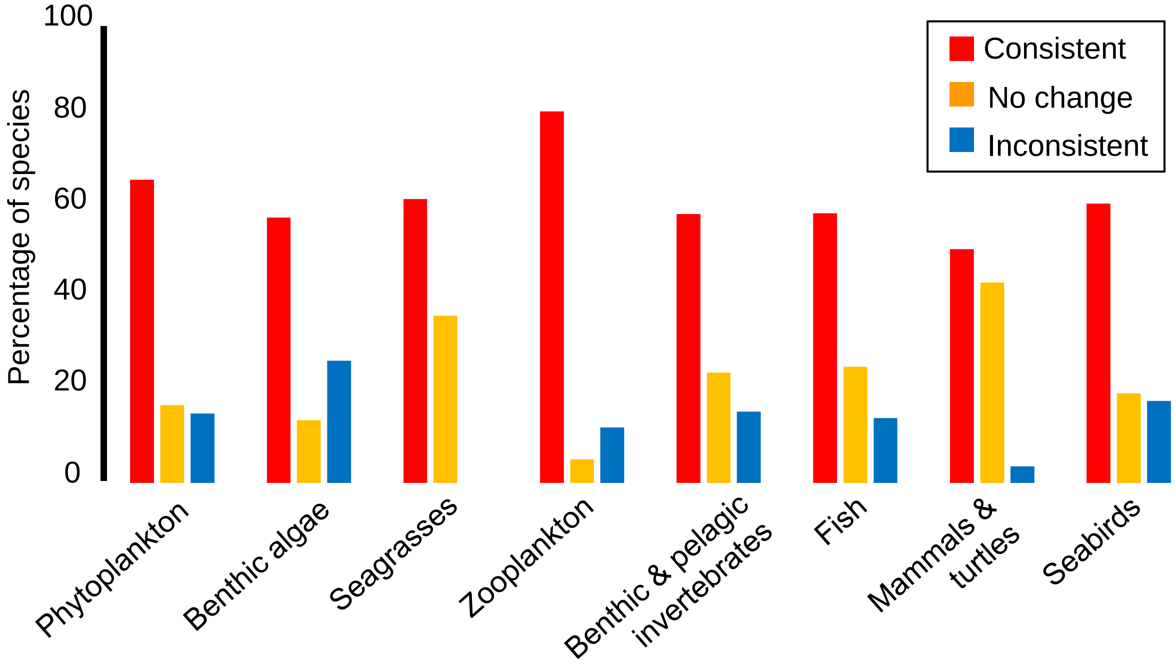

Figure 3. Species responses to climate warming

Most species across all major study groups have shown responses consistent with warming; data include 1774 responses from 196 papers, mainly from Poloczanka et al. (2013)

2.3 Future Projections of Biodiversity Change

Species distribution modelling using ‘bioclimate envelope’ approaches is commonly used to project the future distributions of marine organisms in a future climate (Elith and Leathwick, 2009). Briefly, this approach quantifies relationships between species presence and recent environmental measurements, and uses that information to project distributions using modelled environmental information under future emission scenarios (Elith and Leathwick, 2009). The approach may also take into consideration population growth rates, larval dispersal and adult migration (Cheung et al. 2009). Where these approaches have been used to assess changes to future diversity, they have consistently predicted substantial changes in marine biodiversity over the next 50–100 years (Cheung et al. 2009). Rapid range shifts greater than 4 km per year are projected over this timescale for many marine species, with the more-rapid shifts predicted for open water pelagic species than demersal species, owing to higher potential motility (Pereira et al. 2010). However, predictions from bioclimate envelope approaches must be treated with caution, as they typically only include a subset of factors that affect distributions, and often necessarily overlook interactions with other species (predators, prey and pathogens) and species dependency on very specific but often unmeasured habitat variables.

3. Ocean Warming and Capture Fisheries

Globally, capture fisheries production has flatlined, and most stocks are considered maximally exploited or overexploited (Pauly and Froese 2012; Costello et al. 2016). Analyses of the species composition of fisheries worldwide indicates that there has been a steady ‘tropicalisation’ of the catch (higher proportion of warm water species) due to increasing sea surface temperatures shifting fishes to higher latitude (Cheung et al. 2013).

3.1 UK Capture Fisheries

The UK capture fishery sector is divided into 'demersal' fisheries targeting bottom-living fishes such as cod and plaice, 'pelagic' fisheries targeting open-sea fishes such as herring and mackerel, and shellfisheries that target crab, scallops and *Nephrops* (scampi or langoustine). In 2015, landings of these sectors were: demersal fisheries 168,800 tonnes valued at £293.3 million at port; pelagic fisheries 389,800 tonnes valued at £206.6 million; and shellfisheries 149,500 tonnes valued at £275.2 million (Marine Management Organisation 2016).

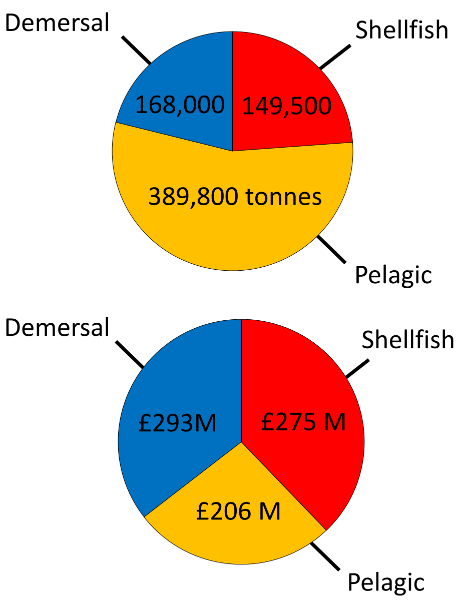

Figure 4. UK capture fisheries landings and value at port in 2015

Source: Marine Management Organisation (2016)

3.2 UK Fisheries and Warming Seas

The size of UK fish and shellfish stocks is intrinsically tied to fishing pressure, but fishing and climate change interact in multiple ways, and they should not be considered independent issues (Brander 2007). We have high confidence that warming has influenced the abundance and distributions of commercially fished stocks across the region. Over the last 20 years, there have been new or expanding fisheries for warmer water species such as seabass (*Dicentrarchus labrax*) and red mullet (*Mullus surmuletus*) (Pinnegar et al. 2013).

Simpson et al. (2011) compiled long-term data (1980–2008) from survey hauls across the European continental shelf, which showed abundance of 72 per cent of demersal species was significantly related to temperature changes. Abundance responses were strongly associated with thermal preference of the species. Species responses to temperature were strong predictors of trends in commercial landings, with those species preferring warmer waters also increasing in catches.

Montero-Serra (2015) compiled data from 1972 and 2012 on the six most commercially important pelagic species in the North Sea. All six of the major UK pelagic species were dependent on temperature, and those species preferring warmer waters became more common in the region.

Abundance of shellfish populations in UK waters have been linked with temperature. Juvenile scallop abundance in the Isle of Man fishery increased with warming (Shephard et al. 2010).

Mechanisms that lead temperature to affect population size are uncertain in most cases. In Atlantic cod (*Gadus morhua*) in the North Sea, warming seas have delayed the arrival of the favoured prey of planktonic larval cod, the copepod *Calanus finmarchicus*, resulting in periods of failed recruitment (Beaugrand et al. 2003).

3.3 Implications of Warming for Future Fisheries Production

Projections of future fish biomass and distributions have been made using two complementary methods. Process-based model capture inferred ecological processes, such as the energy flow between plankton and fish populations (Cheung et al. 2011; Blanchard et al. 2012; Barange et al. 2014). Statistical models capture more direct associations of stock distribution or abundance with environmental variables based on past observational data (Jones et al. 2012; Rutterford et al. 2015).

Rutterford et al. (2015) studied eight demersal North Sea species using a statistical model, and found that species were unlikely to move north to cooler waters, due to their dependence on non-thermal resources (for example water, suitable depth and substrate). This work suggested that ‘new’ demersal fisheries are unlikely to arise, but existing fished species may expand or contract in fisheries importance locally, depending on the thermal preferences of the species.

To estimate the future financial implications of warming to the UK fisheries, Fernandes et al. (2016) combined ocean warming and ocean acidification projections with experimental data in a process-based model. They estimated that warming will lead to substantial declines in UK catches of demersal, shellfish and pelagic fishes by 2050, with losses projected to be ~£87 million per annum compared to the present day for fishing and associated sectors. In total they estimated climate change would drive a 6.8 per cent loss by 2050 of the £1,268 million of annual revenue attributable to the industry (in 2011).

There are various factors contributing to this loss but one of the main drivers is the decrease in primary productivity due to projected increases in temperature.

Global-scale analyses using process-based models estimated that global fish production in capture fisheries may increase on average by 3.4 per cent from present yield by 2050 (Barange et al. 2014), and there may be a global reorganisation of stocks as a consequence of climate change over the same period (Cheung et al. 2010).

European Union policies have helped many stocks from the European continental shelf recover over the last decade (Cardinale et al. 2013), which may help in their resilience to climate change. However at present we have low confidence in predictions of fish abundances and dependent fisheries, due to inconsistent results among models (Jones et al. 2012; Pinnegar et al. 2013), and a lack of comprehensive studies that have addressed the issue. There is a need to further develop and validate spatially-resolved statistical models of future stock sizes of key UK capture fisheries species within projected regional climate and fisheries scenarios. This will enable predictions of changes to UK fisheries over economically relevant timescales within the next century.

4. Ocean Warming and Aquaculture

Increasing demand for fish protein has resulted in major increase in aquaculture in both marine and freshwater environments, and it is now the fastest growing of the major food sectors (Troell et al. 2014). Threats to aquaculture from climate change include increased storm damage and changes to rainfall patterns that affect run off into inshore marine habitats. The effects of warming seas on marine aquaculture are largely unclear, but there are concerns that the temperature rises will affect the suitability of areas for growing particular species and reduce feed intake and food conversion efficiency (Gubbins 2006). Warming seas can also influence the prevalence of disease (Bell et al. 2013), by increasing parasite growth rates, promoting the geographic spread of novel pathogens (Harvell et al. 2002; Brander 2007), or by reducing the immunocompetence of the farmed species (Callaway et al. 2012).

4.1 The UK Aquaculture Industry

The UK aquaculture industry is divided into two statistical units; finfish and shellfish. In 2012, finfish production was estimated at 177,780 tonnes and valued at £555 million. The vast majority of this was the marine culture of Atlantic salmon (*Salmo salar*), estimated to be 162,220 tonnes and valued at £519 million, mainly from Scottish producers (Ellis et al. 2015). In 2012, shellfish production was estimated at 27,360 tonnes and valued at £33 million. The majority of this was marine culture of blue mussel (*Mytilus edulis*), estimated to be 26,021 tonnes, valued at £27 million (Ellis et al. 2015). Effects of climate change on aquaculture production is likely to depend on thermal affinities of species, and to the proximity of aquaculture locations to equatorward range boundaries. For both Atlantic salmon and blue mussel, the UK is close to European southern range boundaries.

4.2 UK Aquaculture and Warming Seas

Experimental and observational work has demonstrated substantial effects of temperature on growth and reproduction of farmed species (e.g. Elliott and Elliott 2010). However, evidence describing how temperature affects production in commercial systems, either directly by affecting an individual’s physiology, or indirectly by affecting pathogens, parasites or predators is rare in the peer-reviewed literature.

There is evidence of thermal effects on species within farmed systems, which could potentially affect production. Behavioural research shows Atlantic salmon actively prefer to occupy a 16–18°C temperature zone within aquaculture cages, and they display an active avoidance of water warmer than 18°C (Oppedal et al. 2011). This matches evidence that the optimal temperature range for growth of Atlantic salmon in seawater is 14–18°C (Jobling 1981; Johansson et al. 2009), and that there are reductions in performance by 20–25 per cent when temperatures reach 16–20°C (Oppedal et al. 2011). We estimate summer sea temperatures consistently exceeding 18°C in Scotland by 2050 under the RCP8.5 emissions scenario, and may be avoided under the less extreme RCP2.6 scenario. Rising sea temperatures could also drive increases in hypoxia within sea cages, due to reduced dissolved oxygen in warmer water, further impairing performance (Oppedal et al. 2011).

The impacts of temperature change on blue mussel production in Strangford Lough, Northern Ireland, have been modelled. Here, future rises in average water temperature of 1°C are predicted to lead to a 50 per cent loss of mussel production, while an average rise of 4°C would lead to a production loss of 70 per cent (Ferreira et al. 2008). In Northern Ireland these conditions are expected by 2030 and 2100, respectively, under the RCP8.5 emissions scenario, and may be largely avoided under the less extreme RCP2.6 scenario. Over recent years the Mediterranean mussel *M. galloprovincialis* has been found in northern European waters, often with *M. edulis x M. galloprovincialis hybrids* (Dias et al. 2009; Mathiesen et al. 2017). The presence of this typically southern European species has been attributed to human activities, such as ship traffic (Mathieson et al. 2017). It is possible that *M. galloprovincialis* and their hybrids may become favoured by selection with projected temperature increases around UK waters.

4.3 Implications of Warming for Future Aquaculture Production

In addition to direct evidence of temperature on marine aquaculture species, there is a need for further information on effects of temperature on parasites, pathogens and organisms that foul cages.

Key parasites of Atlantic salmon include the sea lice (*Lepeophtheirus salmonis* and *Caligus elongatus*). In 2006 they were estimated to cost the industry £28.6 million per year (Euro 33.6 million) in lost production and parasiticide use (Costello 2009). Their early life history is known to be temperate dependent, with shorter generation times in warmer waters, thus future sea-lice infestations are potentially greater than currently observed and treated (Costello 2006).

Mytilicola intestinalis is a copepod parasite of the mussel *Mytilus edulis*, and is known to depress feeding performance at water temperatures of 22–23°C in UK waters, reducing scope for growth in summer temperatures (Bayne et al. 1978). We estimate summer sea temperatures consistently exceeding 22°C by 2050 under the RCP8.5 emissions scenario, but may be avoided under the less extreme RCP2.6 scenario. Thus, future production may be reduced in systems affected by *Mytilicola*, leading to lower mussel production in aquaculture systems.

Warming seas may allow the introduction, establishment and spread of new pathogenic parasites. For example, in North America warmer winters have encouraged the spread of protozoan parasites that caused mass mortality in Eastern oysters (Hofmann et al. 2001). They may also facilitate the dispersal and spread of non-native species that foul cages and block water flow, such as the tunicate *Styela clava* (Cook et al. 2013).

There are concerns that warming seas will increase risks to aquaculture from harmful algal blooms, jellyfish poisoning and the incidence of bacterial diseases that infect shellfish, for example *Vibrio* species, that are also harmful to human health when ingested (Callaway et al. 2012).

Further research is required to project how future sea temperatures will influence production of current UK aquaculture species, and how warming seas will provide opportunities for new aquaculture species. Reviews describing the impacts of warming on aquaculture systems are largely limited to highlighting potential effects (e.g. Callaway et al. 2012), rather than describing evidence from observed changes, or estimating economic impacts. As a consequence we have low confidence in current predictions of future climate effects on UK aquaculture production or value.

5. Ocean Warming and Conservation

Evidence that ocean warming affects population distributions and abundance has implications for conservation and management. In the UK there is evidence that warming has influenced abundance changes of key species of conservation importance, such as seabirds (Daunt and Mitchell 2013). Warming responses can be complex and affect both individual species and whole species assemblages, and can be observed taking place over very short time periods. For example, recent work demonstrated that temperate coastal waters of Western Australia underwent a major regime shift to warmer summers in 2011, resulting in replacement of kelp forest with seaweed turf. This was due to large increases in abundance of herbivorous fish species that were previously rare in the community, and now prevent any reestablishment of kelp (Wernberg et al. 2016).

5.1 Legislation Considering Marine Conservation and Warming

Frost et al. (2016) consider the marine biodiversity legislation focusing on, but not restricted to, UK waters. Of the 21 obligations that Frost et al. considered, only three had explicit reference to climate change, of which two were climate-specific (Climate Change Act of 2008; Climate Change Scotland Act 2009). Nevertheless, many of the obligations require consideration of environmental change, and include mechanisms that allow climate change variables to be addressed. Obligations containing reference to environmental change include the EU Water Framework Directive adopted in 2000 and EU Marine Strategy Framework Directive adopted in 2008, may require assessment with regard to UK legislation in the near future.

The UK's obligation to the Convention on Biological Diversity (1992–1993) is relevant to marine environments in the UK and British Overseas Territories (BOT), and requires that signatories "create national plans, strategies or programs for conservation and sustainable use" and "inventory and monitor biodiversity within their own territories". De Fontaubert et al. (1996) describe good practice to implement the Convention, including consideration of climate impacts within these plans.

5.2 Marine Conservation in the UK and Overseas Territories

UK marine biodiversity legislation focuses primarily on the protection of habitat or species, and has a strong focus on Marine Protected Areas (MPAs). Frost et al. (2016) considered the 'features' that have resulted in MPA designation in UK waters, such as horse mussel (*Modiolus modiolus*) beds that provide a structural habitat for many other species. They suggest these areas could help to mitigate climate change by promoting resilience to climate effects through high biodiversity, as well as reducing non-climate stressors (e.g. fishing and habitat disturbance), and providing corridors for facilitating range shifts.

Modelling suggests there may be substantial warming-related changes to habitat within MPAs by 2100, which may lead to their locations being suboptimal for the target 'feature' species or habitats (Gormley et al. 2013).

A fundamental change to the ecological niches present within MPAs has the potential to lead to larger-scale biodiversity loss. The potential cost of losing the goods and services provided by these habitats requires further evaluation.

Important marine habitats in the BOT are the coral reefs systems within the Chagos archipelago and Pitcairn Island MPAs (Figure 1). These are among the largest of all marine reserves, representing 640,000 km^2 and 834,000 $km,^2$ respectively. These sites are globally recognised for their important biodiversity, but they also have considerable economic relevance for the regions. It has been estimated that the Chagos MPA may support South-West Indian Ocean fisheries outside of the immediate territory by £750 million per annum (Gravestock and Sheppard 2015).

Coral reef habitat within UK BOT is threatened by coral bleaching caused by warming seas. Indo-Pacific reefs have experienced repeated periods of bleaching during years of high sea surface temperature within the Indian Ocean over the last two decades (see e.g. Sheppard et al. 2008).

Nearly all coral reefs are projected to be subject to bleaching on an annual basis by 2080 and 2050 under the RCP2.6 and RPC8.5 scenarios, respectively (van Hooidonk et al. 2013). This suggests that reef-building corals will have to acclimatise or adapt to thermal stress if they are to persist (e.g. Guest et al. 2012). Loss of coral may have considerable implications for regional fisheries, and it has been estimated that bleaching will drive a 30 per cent loss in the value of the commercial coral-associated fisheries elsewhere in the Indo-Pacific (Oxford Economics 2009).

6. Emerging Issues

Ocean warming is driving changes, but biological effects are difficult to predict due to the complexity of ecological communities. Successful projections of future species abundance will need to consider interactions of warming seas with other stressors. These include ocean acidification, rising sea levels, eutrophication, changing rainfall patterns, and fisheries (Cheung et al. 2016).

Most studies of marine biological responses to changing sea temperatures consider long-term changes in average temperature, and more rarely discrete extreme events (Wernberg et al. 2013). We require a better understanding of how extreme temperatures affect UK marine species, including key species for fisheries and aquaculture.

Increased transportation is driving a global homogenisation of marine biological communities, and warming seas may facilitate invasions of new species with potentially detrimental effects to indigenous species (Seebens et al. 2016). Several coastal species that have been established in UK waters for some time have undergone expansions as waters have warmed over recent decades, for example the Chinese mitten crab (*Eriocheir sinensis*) and Japanese wireweed (*Sargassum muticum*) (Reid et al. 2009). There are also species predicted to colonise UK waters in coming decades (Roy et al. 2014). These include the veined rapana whelk (*Rapana venosa*) from subtropical Pacific waters that has colonised the Black Sea and Mediterranean through ballast water. The species is a predator of bivalves and could impact on UK mussel, oyster and cockle production (Kerckhof et al. 2006). The comb jelly (*Mnemiopsis leidyi*), indigenous to temperate and subtropical waters of the western Atlantic is also predicted to arrive. The species is considered an ecosystem engineer, leading to decreased zooplankton production, and reduced biomass of the planktivorous fish that depend upon them (Shiganova et al. 2003).

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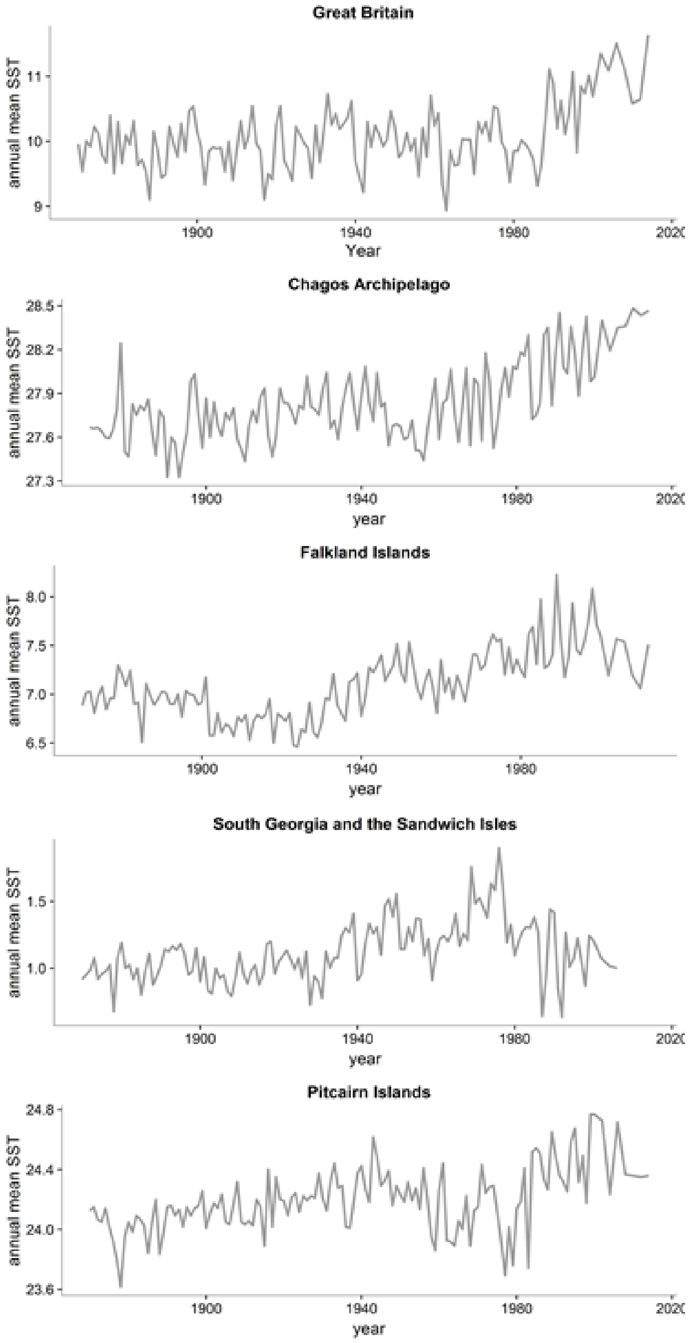
Appendix



Hadley Centre Global Sea Ice and Sea Surface Temperature: Observed sea surface temperatures in UK waters and British Overseas Territories for the period 1870–2014 (also indicated in Figure 1)

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