Explaining Ocean Warming:
Causes, scale, effects and consequences
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“Marine fishes have been responding to ocean warming in multi-faceted ways, from range shift, changes in community structure, phenology, to reduction in body size. These responses are challenging the conservation of marine fishes and add to other existing pressures from human activities.”

“In particular, the increased likelihood of abrupt and unpredictable changes in the productive potential and migratory behaviour of exploited fish stocks may threaten to disrupt cooperative management arrangements.”

Section 3.11 authors
3.11 Impacts and effects of ocean warming on marine fishes

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Summary

• Marine fishes are sensitive to sea water temperature changes because their physiological performance is largely dependent on environmental temperature.
• Fishes that are tropical or polar, and fish in their early life stages are generally most sensitive to ocean warming because they have narrower temperature tolerance ranges.
• Fishes respond to ocean warming by modifying their distributions such that it offers habitats with suitable temperature for them to live. Observation so far suggest fishes have shifted their ranges by 10s to 100s of km as the ocean has warmed.
• Fish communities are altered as their component species shift their distribution under ocean warming, with an increase, outside the tropics, of warmer-water fishes through invasions and a decrease of cold-water species, while warm-water adapted species decreases in abundance in tropical areas as temperature increase. Thus, the tropics are hotspots of ocean warming-driven local extinctions.
• Ocean warming is modifying the seasonality of occurrence of biological events such as spawning and migration. This affects fish because of mismatch in the timing of availability of their prey.
• Maximum body size of fishes may decrease under ocean warming.
• Other non-climate human stressors such as fishing and pollution will interact with climate-induced changes in fish populations, increasing the sensitivity of marine fishes to climate stressors.
• The most direct way of reducing impacts from climate change on fishes is through mitigation of greenhouse gas emission. Simultaneously, climate risk-reduction measures are needed; these include reducing other non-climate human stressors, monitoring of responses of marine fish to a changing ocean, and adapting conservation measures to these responses.
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#### 3.11.1 Introduction

There are approximately 15,000 species of marine fishes in the ocean (Froese and Pauly, 2016). They inhabit almost all parts of the ocean from the surface water, to the deep sea, from coral reefs to seamounts (Cheung et al., 2005). They are also important to the wellbeing of human society through contributing to the economy, food security and culture (see Section 4.5). In the 2000s, fish contributed over 90 million tonnes to marine fisheries catches (Pauly and Zeller, 2016), i.e. 85% of the total marine catch. Moreover, recreational fishing accounted for catching almost 1 million tonnes of fish per year in the 2000s. In addition, marine fish are an essential part of many traditional cultures, e.g. Pacific salmon and herring for First Nations in British Columbia, Canada (Lepofsky and Caldwell, 2013), reef fishes for South Pacific Islanders (Figure 3.11.1) (Zeller et al., 2015).

Climate change adds to the multitude of conservation challenges facing marine fishes from human activities, notably overfishing, habitat destruction and pollution (Dulvy et al., 2003; Pitcher and Cheung, 2013; Sadovy de Mitcheson et al., 2013). Ocean properties have been changing because of greenhouse gas emissions from human activities since the beginning of 20th Century (Stocker et al., 2013). Notably, the ocean has been warming up, becoming more acidic, less oxygenated, and having a reduced ice cover in polar areas (Gattuso et al., 2015). Given the current rate of greenhouse gas emissions, these changes are projected to continue (Portner et al., 2014). Marine fish, as water-breathing ectotherms, are physiologically and ecologically sensitive to changes in ocean properties. In addition to climate change, currently, over 550 species of marine fishes and invertebrates are listed as threatened (Critically endangered, Endangered, and Vulnerable) in the IUCN Red List. Of these species, the majority (80%) is threatened by “fishing and harvesting of aquatic resources” (IUCN, 2016). The responses of marine fish to ocean warming will add to and likely exacerbate the impacts from other human drivers.

This section aims to summarize the major effects of ocean warming on marine fishes and the implications for their conservation status. The section will focus on ocean warming as a driver of changes and its potential interactions with the carbon dioxide–related drivers such as ocean acidification. Firstly, we summarize the key mechanisms that make marine fishes vulnerable.

![Figure 3.11.1 Fishing in Port Vila lagoon, Vanuatu. © Louisa Cass / AusAID.](image-url)
to changes in ocean properties. Secondly, we highlight the main biological and ecological responses of marine fishes to these environmental changes, and the resulting impacts on fish populations and communities. Finally, we discuss the key challenges and opportunities for conservation of marine fishes under climate change.

### 3.11.2 Mechanisms of climate change effects on marine fishes

The responses of marine fishes to changes in ocean temperature can be predicted from their physiology of thermal tolerance and oxygen capacity. Physiological performance of marine fishes is dependent on the their temperature preferences and tolerance limits (Pörtner and Farrell, 2008). Performance of body functions such as growth and reproduction are optimal within a certain temperature range (Figure 3.11.2). Performance decreases when temperature increases or decreases from the preferred temperature, and when temperature is beyond the temperature tolerance limits of the species, body functions are halted and survival is compromised. As body temperature, in fish, is dependent on environmental temperature, ocean warming affects the basic body functions of fish.

Different fish species and life stages can have different temperature tolerance ranges. Polar species that are adapted to the stable and cold polar environment generally have a narrower thermal window (Figure 3.11.2b). For example, some polar species e.g. Antarctic nototheniid fish have adapted to stable cold polar environments, leading to fewer red blood cells, oxygen binding proteins (Pörtner, 2002), and enzymes that are especially sensitive to temperature. Similarly, tropical species that inhabit warm waters tend to have a narrower thermal window, compared to temperate fishes that live in an environment with large seasonal temperature changes (Pauly, 2010). In addition, larval and spawning fishes have greater temperature sensitivity, rendering the early life stages of fishes more vulnerable to ocean warming.

Understanding marine organisms’ thermal tolerances and the geographic pattern of climate change help explain and predict their survival and distribution under changing climate. Optimal foraging theory predicts that fishes tend to be distributed in environments that maximize their growth and reproduction. Thus, as the ocean warms, marine fishes respond, as they do in response to seasonal changes in temperature (Pauly, 2010), i.e. by shifting their distribution to maintain themselves in habitats which lie within their preferred temperature limits. Generally, fish are responsive to temperature changes throughout their range (Sunday et al., 2012).

Temperature may also act indirectly on a fishes’ survival and distribution by influencing phenology, dispersal, predation pressure and available food supply. Change in the distribution and abundance of prey and predators affects growth and mortality of other fishes. As temperature affects the rate of egg (Pauly and Pullin, 1988) and larval development (O’Connor et al., 2007), warmer temperatures might also decrease the opportunity for predation at this phase in the life cycle. In addition, as the duration of the larval stage determines the length of time they are subjected to

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**Figure 3.11.2 Relationship between temperature and physiological performance of marine water-breathing ectotherms.** (a) Temperature tolerance decreases with multiple environmental stressors, and (b) temperature sensitivity is dependent on the characteristics of the environmental where organisms are adapted to (Pörtner and Knust, 2007).
movement by ocean currents, increased temperatures will indirectly affect population connectivity, community structure and regional to global patterns of biodiversity (O’Connor et al., 2007). For example, in tropical reef systems, climate-induced increases in ocean temperature and reduced food supply will severely impact larval fishes (McLeod et al., 2013). In addition, critical habitats of marine fishes, such as coral reefs (Figure 3.11.3), are extremely sensitive to ocean warming, notably through coral bleaching (see Section 3.8).

### 3.11.3 Observed responses of marine fishes to warming

#### 3.11.3.1 Species range shift

Observations and theory have indicated that marine fishes frequently undergo shifts in distribution in response to changing ocean temperature. Under ocean warming, range shifts are most commonly towards higher latitudes (Perry et al., 2005; Hiddink and Ter Hofstede, 2008; Poloczanska et al., 2013), deeper waters (Dulvy et al., 2008), and in general, following temperature velocity (Pinsky et al., 2013) (Box 3.11.1). Meta-analyses of observed range shift in the last decades have shown that fishes are moving poleward, on average, at rates of 10s of km per decade (Poloczanska et al., 2013) (Figure 3.11.4). Also, analysis of survey data further shows that range shifts for fishes in North American shelf seas in the last few decades are

![Figure 3.11.3 Bigeye trevally over healthy reef in Tubbataha National Park, Philippines. © Steve De Neef.](image-url)

![Figure 3.11.4 Meta-analysis of observed range shift for marine species (from Poloczanska et al., 2013).](image-url)
Box 3.11.1 Multi-facet responses of marine fishes to ocean warming: a case study in the Northeast Atlantic Ocean

Marine fishes in the North-east Atlantic Ocean have responded to ocean warming through changes in distributions, phenology and body size. Sea Surface Temperature (SST) in the NE Atlantic has been increasing in recent decades e.g., sea surface temperature in the North Sea and Norwegian Sea increased by 1.31°C and 0.85°C between 1982 and 2006. Amongst the 50 abundant fish species in the waters in the North-east Atlantic, 70% of the species responded to warming in the region by changing distribution and abundance between 1980 and 2008, resulting in increasing changes in species assemblages as temperature increases (Simpson et al., 2011). Simultaneously, the mean temperature of catch (MTC) in the North Sea increased significantly during this period, indicating an increase in dominance of warmer water species in the fisheries catches (Cheung et al., 2013a). For example, based on data since the early 20th Century, distribution of North Sea Atlantic cod (Figure 1) shifted poleward by 3.74°N and to deeper water by 54.2 m per degree Celsius of increase in SST (Engelhardt et al., 2014). Also, eight fish species in the North Sea show a decrease in maximum body size that is related to a 1-2°C increase in sea water temperature (Baudron et al., 2014). Specifically, maximum body size of northern haddock stock was found to decrease by 29% between 1975 (average of 1973 – 1977) and 1995 (average of 1993 – 1997) (Baudron et al., 2014). Moreover, increases in sea surface temperature affect the timing and magnitude of growth, recruitment and migration (Jansen and Gislason, 2011). Given continuous warming of the oceans under climate change, the trends described above will continue. For example, using a computer simulation model, 17 fishes in the North Sea are projected to continue to shift poleward at a rate of around 27 km per decade from 1905 to 2050 under a high greenhouse gas emission scenario (Jones et al., 2015). These multi-facet responses of marine fishes to ocean warming may lead to impacts from species to ecosystem levels that are not yet fully understood.

In directions consistent with gradients of temperature changes (Pinsky et al., 2013).

Although the biogeographical responses of fishes to ocean warming are similar, their sensitivity to temperature varies between species. The differences in sensitivity can be due to different mobility, life history stages, biological characteristics and habitats. This may limit the ability of the species to keep pace with ocean warming (Hiddink et al., 2012). Also, fish species with large body size, high swimming ability, large size at settlement and pelagic spawning behaviour are also found to be more successful at colonizing temperate habitats, while habitat and food limitation during juvenile stages may constrain movement (Feary et al., 2014). Genetic bottlenecks can emerge where species exhibit limited dispersal capacity due to a lack of suitable habitat, thereby preventing population connectivity, e.g., lack of gene flow between populations of corkwing wrasse, Symphodus melops (Figure 3.11.5), in the North Sea and Portugal (Knutsen et al., 2013). In some cases, geographical and oceanographic features act as barriers to distribution shift, e.g. landmass in semi-enclosed seas such as the Mediterranean Sea (Ben Rais Lasram et al., 2010) or depth in the North Sea for demersal fishes (Rutterford et al., 2015).
3.11.3.2 Shifts in community structure

The composition of fish community will be altered as species shift their distribution under ocean warming. Generally, increase in ocean temperature results in increase in dominance of warmer water species in the fish community (Cheung et al., 2013a; Stuart-Smith et al., 2015). For example, on the European continental shelf, a response to warming has been demonstrated in the abundances of 72% of the 50 most common fish species inhabiting UK waters (Simpson et al., 2011) (Box 3.11.1). These shifts reflect the influx of warmer-water adapted marine species to regions with colder waters that have also been observed elsewhere (Arvedlund and Kavanagh, 2009; Fodrie et al., 2010). Arctic and tropical fishes have been found occupying new habitats as temperature changes. A heat wave event in western Australia was found to alter biodiversity of demersal fish, leading to a tropicalization of community structure (Wernberg et al., 2013; Thomson et al., 2014).

Subtropicalization of European pelagic fish communities has also been observed in the North Sea and Baltic Sea, with shifts from Atlantic herring (Figure 3.11.6a) and European sprat (1960s to 1980s) to Atlantic mackerel, Atlantic horse mackerel, European pilchard (Figure 3.11.6b), and European anchovy (1990s onwards) in response to warming, with sea surface temperature increasing at around 0.02°C yr⁻¹ (Montero-Serra et al., 2015), while the fish communities of the Eastern Mediterranean are increasingly dominated by fishes with warm-water affinities (Stergiou and Tsikliras, 2011; Keskin and Pauly, 2014). Global fisheries catch data, since the early 1970s are also increasingly dominated by warmer water species (Cheung et al., 2013a). This is indicated by an increase in the Mean Temperature of Catch (MTC) – an indicator representing the mean temperature preference of species in annual fisheries catches weighted by their catch amount. Therefore, if catches are increasingly dominated by warmer water species, MTC increases as well. The observed changes in MTC from 1970 - 2006 are related to increase in sea surface temperature in the same period (Figure 3.11.7). However, in tropical areas, after the initial reduction in the abundance of subtropical species’ catches, scope for further tropicalization of communities became limited (Figure 3.11.7).

Range shifts for fishes and invertebrates are projected to continue in the 21st Century under climate change (Cheung et al., 2009; Jones and Cheung, 2015). Although in temperate climates, local extinctions may be compensated for by local invasions as species move into newly suitable habitat, thereby leading to an overall change in community structure, tropical regions may see declines in species richness as the scope for community tropicalization is reached. For example, projections of distributions for over 800 exploited fishes and invertebrates using multiple species distribution models result in a predicted average poleward latitudinal range shift of 10s to 100s km per decade under a high greenhouse gas emission scenario (Jones and Cheung, 2015). This rate of shift is consistent with observed rates of shift in the 20th Century (Poloczanska et al., 2013). Such predicted distribution shifts resulted in large-scale changes in patterns of species richness through species invasions (occurring in new areas) and local extinctions (disappearing from previously occurring areas) (Figure 3.11.8). Hotspots of high local invasion are common in high latitude regions, while local extinctions are concentrated near the equator. The shifts in fish distributions may result in fish communities that are different from those previously observed (Molinos et al., 2015).

Figure 3.11.6 a) Atlantic herring. © Dirk Schories, b) European pilchard. © Alessandro Duci.
Species range shifts can affect trophic interactions and the functioning of marine ecosystems. Species that increase in abundance may increase predation, grazing or competition with existing species. On the other hand, species may lose important food sources when prey species shift away from an ecosystem. For example, the tropicalization of temperate marine ecosystems through poleward range shifts of tropical fish grazers is shown to increase the grazing rate of temperate macroalgae (Vergés et al., 2014). Such trophic impacts resulting from climate-induced range shifts are expected to affect ecosystem structure and dynamics in temperate reefs. Altered interspecific interactions between sympatric coastal fishes were observed in the Mediterranean under warmer conditions, with a cooler-water fish (e.g. rainbow wrasse, *Coris julis*; Figure 3.11.9a) being displaced by a more dominant warmer-water fish (e.g. ornate wrasse, *Thalassoma pavo*; Figure 3.11.9b) (Milazzo et al., 2013). This example supports the theory that there will be ‘winners’ and ‘losers’ under climate change, with warm-adapted species outcompeting cold-adapted species in temperate marine ecosystems.

### 3.11.3.3 Changes in phenology

Climate change modifies phenology (i.e. periodic biological phenomena), of marine fishes so that critical phases remain synchronized with climatic alterations. For example, spawning season for 27 species in the North Sea have been shown to be negatively correlated with the mean sea surface temperature (SST) in the preceding winter (Greve et al., 2005), while earlier spring migrations have also been noted (Sims et al., 2001). Phenological responses are highly taxon- or species-specific, resulting from sensitivity to climatic fluctuations as well as factors such as temperature, light, or food availability (Edwards and Richardson, 2004). A meta-analysis of observed phenological shifts suggested that seasonal events of marine species advanced by an average of 4.4 days per decade during the late 20th Century (Poloczanska et al., 2013). Also, larvae of 17 of the 43 species of fish species in the California Current
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Figure 3.11.8 Projected intensity of (a) local extinction and (b) species invasion between 2000 and 2050 under the RCP 8.5 scenario (from Jones and Cheung, 2015). The unit is expressed as number of species locally extinct or invaded relative to the original species richness.
ecosystem occurred earlier in recent decades relative to the last 58 years (Asch, 2015). However, zooplankton, being one of the main food items for these fishes, did not shift their phenology synchronously with most fishes (Asch, 2015). Such a mismatch may affect the availability of food for fishes. Altered phenology and timing of development may also lead to altered dispersal. For species whose offspring develop in the water column, for example, the duration of the larval stage will decrease with warmer temperatures. This determines the length of time larvae are subject to movement by ocean currents and thus affects the habitat that the larvae could reach (O’Connor et al., 2007).

### 3.11.3.4 Changes in body size

Both theory and empirical observations further support the hypothesis that warming and reduced oxygen will reduce the body size of marine fishes (Pauly, 1998a) and invertebrates, such as squids (Pauly, 1998b). The preferred minimum oxygen tolerance threshold of an organism varies across species, body size, and life stage, and is highest for large organisms. As fish increase in size (weight), mass-specific oxygen demand increases more rapidly than oxygen supply which occurs via the surface of the gills (Pauly, 1998a, b). Thus, while fish reach a maximum body size when oxygen supply is balanced...
by oxygen demand (Figure 3.11.10a), maximum body size decreases when temperature increases (Figure 3.11.10b). The decrease in food conversion efficiency that this implies, all else being equal, (Pauly, 2010) decreases the biomass production of fish and invertebrate populations.

Simulation model projections structured around Figure 3.11.10 suggest decreases in the maximum body size of fishes under scenarios of ocean warming and decreasing dissolved oxygen levels. Specifically, the integrated biological responses of over 600 species of marine fishes due to changes in distribution, abundance and body size were examined, based on explicit representations of ecophysiology, dispersal, distribution, and population dynamics (Cheung et al., 2013b). The result was that assemblage-averaged maximum body weight is expected to shrink by 14–24% globally from 2000 to 2050 under a high-emission scenario. The projected magnitude of decrease in body size is consistent with experimental (Forster et al., 2012; Cheung et al., 2013b) and field observations (Baudron et al., 2014) (Box 3.11.1). About half of this shrinkage is due to change in distribution and abundance, the remainder to changes in physiological performance as illustrated in Figure 3.11.10. The tropical and intermediate latitudinal areas will be heavily impacted. Decreases in growth and body size are likely to reduce the biomass production of fish populations, and hence fisheries catches, and potentially alter trophic interactions.

3.11.4 Interactions with other human drivers
The main non-climate anthropogenic stressors will interact with climate-induced changes in fish populations (Planque et al., 2010), increasing the sensitivity of marine fishes to climate stressors. For example, intensive fishing leads to the depletion of large predatory species and the truncated age-structure in targeted populations, with an increased dominance of juveniles and small-bodied, fast-turnover species. Such communities tend to track changes in ocean conditions more closely (Perry et al., 2010). In Tasmania, biological communities in exploited areas have been shown to be more sensitive to ocean changes relative to areas protected from fishing (Bates et al., 2013). One of the most important pathways of pollution impact on marine organisms is also through nutrient enrichment from the discharge of sewage, and agricultural and industrial waste into the ocean, ultimately leading to oxygen depletion (Diaz and Rosenberg, 2008), thereby rendering marine organisms more vulnerable to ocean warming. Globally, 94% of the low oxygen “dead zones” are in areas where temperature is projected to increase by 2°C by the end of the century under the business-as-usual emissions scenario (Altieri and Gedan, 2015). Habitat degradation from other human stressors may exacerbate climate change impacts through modification of critical habitats that some fishes depend on. Depletion or local extinction of sub-populations may reduce standing genetic diversity that is important for marine fishes to adapt to the changing climate.

3.11.5 Scope for genetic adaptation
The capacity for species to acclimate or adapt to ocean warming is still uncertain, but studies have increasingly explored the feasibility and implications of genetic and phenotypic responses (Munday et al., 2013). While evolutionary adaptation to ocean warming has been shown to be possible in principle (Muñoz et al., 2014), evolutionary trade-offs and temporal variability make it difficult to assess the degree to which adaptation can be deemed ‘successful’ (Sunday et al., 2014). For instance, rapid transgenerational acclimation to increases in water temperature has been exhibited by reef fish (e.g. the spiny chromis, Acanthochromis polyacanthus; Figure 3.11.11) (Donelson et al., 2011). Although this may suggest the capacity for species to mitigate climatic stressors through epigenetics, such adaptation might come at the cost of other attributes or may be inhibited under multiple stressors (Donelson et al., 2011). In particular, some forms of genetic adaptation may in fact be maladaptive (Merilä and Hendry, 2014). Also, the very existence of temperature-mediated seasonal migration in fish suggests that shifts in distributions are more likely than changes in the thermal adaptation of fish.

Figure 3.11.11 Spiny chromis. © Nikita.
3.11.6 Implications for conservation of marine fishes

Effective conservation of fish populations and ecosystems under climate change increases the resilience of ecosystems and the adaptive capacity of management systems, for example by reducing other human perturbations. While contemporary global extinction of marine fishes primarily attributable to climate change does not seem to have occurred yet, mitigating the impacts of climate change on marine fishes should be attempted, notably by reducing stresses from overfishing, habitat degradation, pollution runoff, land-use transformation, and invasive species. As such, effective implementation of ecosystem-based management that considers a much wider range of environmental and human stressors is important to conservation of marine fishes.

The reduced predictability of marine ecosystems due to climate change will make it more difficult to provide accurate assessments of the current and future status of marine fishes. Also, changing baseline oceanographic and ecological conditions may affect the effectiveness of existing conservation and management measures such as marine protected areas (Jones et al., 2013). The application of adaptive management approach (Walters and Martell, 2004) through the incorporation of monitoring programmes that are designed for a changing ocean and the subsequent usage of the data to improve monitoring are thus important (Dunn et al., 2016). Monitoring will include data for indicators at the pressure, state, and response levels, thereby promoting fast decision responses to changing and uncertain conditions and allowing a suite of possible responses to be maintained (Anthony et al., 2015).

Marine protected areas (MPAs), for example, are a major tool to conserve marine biodiversity, and have been shown to enhance population resilience to climate-driven disturbance (Micheli et al., 2012). This applies especially to large and very large MPAs, of which several have lately been declared (Boonzaier and Pauly, 2016). However, climate change-induced changes in species’ distribution shifts may lead to both emigration and immigration of species from or into an MPA. This will alter the specific species assemblage being conserved, potentially losing species of conservation value and reducing the efficacy of the MPA. There is therefore a need to increase the robustness and enhance the resilience of protected areas themselves to climate change. For example, by assessing the degree of future environmental change within proposed protected areas, conservation planning that includes areas where species’ range may shift to could help protect against biodiversity loss (Levy and Ban, 2012). Implementing networks of MPAs may also increase the likelihood of effectively conserving species following climate change-induced range shifts by ensuring that future potential habitats for fishes are protected (McLeod et al., 2009; Gaines et al., 2010).

Long-term observation data and monitoring programmes, essential to detection and attribution of the responses of marine biodiversity to climate change and ocean acidification, are limited globally. It is suggested that time-series that span at least multiple decades are needed to detect long-term trends in the ocean from natural variability (e.g. for net primary production (Henson et al., 2010)). Also, analysis explicitly linking biological responses to environmental change between levels of organization (from individual to ecosystem) is also needed to provide integrated multi-scale understanding of climate change effects on marine biodiversity. The role of evolutionary and phenotypic responses to determining climate change impacts on marine biodiversity is still uncertain. The interaction of multiple anthropogenic threats, and predator-prey interactions further contribute uncertainty to predicting the likely impact of climate change on specific populations and species. For example, both fisheries and warming waters are thought to have caused a decline of sandeels (Figure 3.11.12; mainly Ammodytes marinus) and, in consequence, decline a breeding success of black-legged kittiwakes and common guillemots (MacDonald et al., 2015) (Figures 3.11.13a,b). Disentangling the impact of these threats and projecting possible scenarios of change into the future therefore remains a challenge, despite recent advances in this area.

Figure 3.11.12 Sandeels. © Thomas Warner, DTU Aqua.
Climate change may also affect the effectiveness of conservation and management, thus increasing the risk to marine fishes. In particular, the increased likelihood of abrupt and unpredictable changes in the productive potential and migratory behaviour of exploited fish stocks may threaten to disrupt cooperative management arrangements. For example, the distribution of Atlantic mackerel (*Scomber scombrus*) in the North-east Atlantic Ocean recently shifted northward, probably as a result of changing ocean conditions. The Atlantic mackerel fisheries were believed to be ‘sustainable’, and they were certified by the Marine Stewardship Council. However, following the species’ northward shift to waters around Iceland and the Faroe Islands, these countries unilaterally increased their quota, leading to an international dispute over quota allocations with countries disputing each other’s access to the straddling mackerel stock. This results in destabilization of management of the mackerel fisheries and the suspension of its Marine Stewardship Council certification (Sumaila et al., 2011; Miller et al., 2013). Such disputes are projected to increase as ocean warming increases with climate change.

### 3.11.7 Conclusions and recommendations

Marine fishes have been responding to ocean warming in multi-faceted ways, from range shift, changes in community structure, phenology, to reduction in body size. These responses are challenging the conservation of marine fishes and add to other existing pressures from human activities. The most direct way of reducing impacts from climate change is through mitigation of greenhouse gas emission. Limiting the degree of warming to less than 1.5°C, as noted as a goal in the Paris Agreement, would reduce the level of expected climate change impacts on marine fish in the 21st Century. However, climate change will continue in the next few decades, we need to reduce the resulting conservation risk on marine fish. Climate risk-reduction measures include reducing other non-climate human stressors, continuing monitoring of responses of marine fish to the changing oceans, and allowing existing conservation measures to be adaptable to these responses.

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### 3.11.8 References


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