A review of climate change and the implementation of marine biodiversity legislation in the United Kingdom

Citation for published version:
Frost, M, Bayliss-Brown, G, Buckley, P, Cox, M, Dye, S, Sanderson, W, Stoker, B & Withers Harvey, N 2016, 'A review of climate change and the implementation of marine biodiversity legislation in the United Kingdom', *Aquatic Conservation: Marine and Freshwater Ecosystems*, vol. 26, no. 3, pp. 576–595. https://doi.org/10.1002/aqc.2628

Digital Object Identifier (DOI):
10.1002/aqc.2628

Published In:
Aquatic Conservation: Marine and Freshwater Ecosystems

AQUATIC CONSERVATION: MARINE AND FRESHWATER ECOSYSTEMS

Aquatic Conserv: Mar. Freshw. Ecosyst. (2016)

Published online in Wiley Online Library
(wileyonlinelibrary.com). DOI: 10.1002/aqc.2628

A review of climate change and the implementation of marine biodiversity legislation in the United Kingdom

MATTHEW FROST[a]*, GEORGIA BAYLISS-BROWN[b,i], PAUL BUCKLEY[b], MARTYN COX[c], STEPHEN R. DYE[b,g], WILLIAM G. SANDERSON[d,h], BETHANY STOKER[e] and NARUMON WITHERS HARVEY[f]

[a]*Marine Biological Association of the United Kingdom, Plymouth, UK*

[b]*MCCIP Secretariat, Marine Climate Change Centre, Cefas, Lowestoft, UK*

[c]*Marine Scotland, Scottish Government, Victoria Quay, Edinburgh, UK*

[d]*Centre for Marine Biodiversity and Biotechnology, School of Life Sciences, Heriot-Watt University, Edinburgh, UK*

[e]*Joint Nature Conservation Committee, Peterborough, UK*

[f]*Marine Environmental Strategy and Evidence, Defra, London, UK*

[g]*COAS, School of Environmental Sciences, UEA, Norwich, UK*

[h]*St Abbs Marine Station, St Abbs, Berwickshire, UK*

[i]*AquaTT UETP Ltd, Dublin, Ireland*

ABSTRACT

1. Marine legislation, the key means by which the conservation of marine biodiversity is achieved, has been developing since the 1960s. In recent decades, an increasing focus on 'holistic' policy development is evident, compared with earlier 'piecemeal' sectoral approaches. Important marine legislative tools being used in the United Kingdom, and internationally, include the designation of marine protected areas and the Marine Strategy Framework Directive (MSFD) with its aim of meeting 'Good Environmental Status' (GES) for European seas by 2020.

2. There is growing evidence of climate change impacts on marine biodiversity, which may compromise the effectiveness of any legislation intended to promote sustainable marine resource management.

3. A review of key marine biodiversity legislation relevant to the UK shows climate change was not considered in the drafting of much early legislation. Despite the huge increase in knowledge of climate change impacts in recent decades, legislation is still limited in how it takes these impacts into account. There is scope, however, to account for climate change in implementing much of the legislation through (a) existing references to environmental variability; (b) review cycles; and (c) secondary legislation and complementary policy development.

4. For legislation relating to marine protected areas (e.g. the EC Habitats and Birds Directives), climate change has generally not been considered in the site-designation process, or for ongoing management, with the exception of the Marine (Scotland) Act. Given that changing environmental conditions (e.g. rising temperatures and ocean acidification) directly affect the habitats and species that sites are designated for, how this legislation is used to protect marine biodiversity in a changing climate requires further consideration.

5. Accounting for climate change impacts on marine biodiversity in the development and implementation of legislation is vital to enable timely, adaptive management responses. Marine modelling can play an important role in informing management decisions.

*Correspondence to: Matthew Frost, Marine Biological Association of the United Kingdom, Plymouth, PL1 2 PB, UK. Email: Matfr@mba.ac.uk

Received 23 July 2015; Revised 01 December 2015; Accepted 29 December 2015

KEY WORDS: marine biodiversity; climate change; policy; legislation; United Kingdom; Marine Strategy Framework Directive (MSFD); Good Environmental Status (GES); marine protected areas

INTRODUCTION

Legislation is the key means by which the conservation of marine biodiversity is achieved in order to help ensure the marine environment is used sustainably. Since the 1960s, a raft of legislation has been introduced worldwide covering issues such as marine pollution, conservation of species and habitats and protection of fish stocks (Bell *et al.*, 2013). More recently, the focus has been on establishing protected areas where some or all anthropogenic impacts could be excluded, and through taking a more holistic approach to achieve a desired state across the marine ecosystem. An example of the latter approach would be the Marine Strategy Framework Directive (MSFD) which seeks to establish 'Good Environmental Status' (GES) for European Regional Seas by 2020 (European Commission, 2008; 2008/56/EC).

When considering the effectiveness of legislation for the marine environment it is important to understand ways in which marine ecosystems respond to both natural and anthropogenic changes in climate over a variety of temporal and spatial scales (IPCC (Intergovernmental Panel for Climate Change), 2013). Together these changes provide significant challenges to those setting and implementing legislation for the marine environment, and may have consequences in terms of achieving conservation targets and objectives. The UK policy community has therefore established methods to ensure that up-to-date information on climate change impacts at appropriate spatial and temporal scales is available, such as the reports produced by the UK Marine Climate Change Impacts Partnership (MCCIP, 2006, 2008, 2009, 2010, 2012, 2013). Specific biodiversity related reports such as how wild or farmed fisheries are being affected by climate change are also intended to inform marine policy and management (Callaway *et al.*, 2012; Cheung *et al.*, 2012; Frost *et al.*, 2012; Heath *et al.*, 2012).

It is important to note that anthropogenic climate change is not the only driver of change in the marine environment. Natural climate variability and other anthropogenic pressures (e.g. fishing, nutrient inputs) also affect marine ecosystem resilience and can contribute to ecosystem regime shifts (Möllmann *et al.*, 2011; Parmesan *et al.*, 2013).

The current review provides a brief introduction to general marine biodiversity legislation with some additional consideration of legislation relating to marine protected areas, given this is a major contemporary focus for policymakers in the UK and internationally. Climate change impacts that might have implications for marine biodiversity (and therefore implementation of biodiversity legislation) are then summarized. Finally, the more fundamental issue of whether the potential impacts of climate change are built into current marine biodiversity legislation is examined and the implications for marine biodiversity discussed. The paper uses the United Kingdom (UK) as a case study for the review and examines broad principles that are applicable worldwide.

When discussing legislation it is important to clarify scope and definitions. Although the focus of this paper is on legislation the term 'obligations' is also used (particularly for the analysis) as it has a wider definition. Obligations to conserve biodiversity or to regulate how it is used have their origins at international and national levels and can include: 'conventions', 'legislation' and 'policies'. 'Conventions' are a form of agreement between countries at an international scale, while policy and legislation are generally applied at a national level – though in the UK they may have their origins in European Directives. The term 'legislation' is used specifically to refer to statutory law including both primary legislation (such as Acts of Parliament) and secondary legislation (such as regulations). The term 'policy' is used to describe 'a set of decisions which are oriented towards a long-term purpose or to a particular problem' as defined by the FAO (2015). It is recognized, however, that this distinction is not always clear-cut, as documents outlining policy can be used to form guidance or rules that are in effect legally binding (Bell *et al.*, 2013).

MARINE BIODIVERSITY LEGISLATION

It is beyond the scope of this review to describe all legislation relevant to marine biodiversity; rather, it provides a summary of the development of key marine biodiversity legislation as relevant to the UK and analysed from a climate change perspective; more comprehensive accounts of marine biodiversity legislation in general have been provided elsewhere (e.g. reviews by Hinchen (2014a, b)).

Marine environmental protection issues came to the fore globally during the 1960s (Bell *et al.*, 2013) with the first report on a formal marine policy for UK waters being published in 1969 (NERC and NC, 1969).[1] The vulnerability of marine biodiversity to anthropogenic impacts and the potential need for protection was first highlighted by the Torrey Canyon oil spill in south-west Britain in 1971. A number of reports throughout the 1970s further emphasized the need for a policy on protecting the UK marine environment (NERC, 1973; NCC and NERC, 1979) and in 1981 the UK Wildlife and Countryside Act (WCA) was enacted, which included powers necessary to establish Marine Nature Reserves. The WCA was also used to implement the provisions of the 1979 EC Birds Directive (European Commission, 2009; 2009/147/EC). Throughout the 1980s and 1990s, there was a coordinated effort in the UK to gather evidence to support the implementation of legislation to protect marine biodiversity (Frost and Hawkins, 2007).

[1]A detailed discussion on the development of UK marine policy and related evidence and monitoring needs can be found in Frost and Hawkins (2007) and the history of UK conservation policy is considered by Hiscock (1996).

During the 1990s there was a notable shift towards more significant marine biodiversity obligations being developed both at the European, and wider international level (Frost and Hawkins, 2007). The Convention on Biological Diversity (United Nations, 1992) was an international treaty implemented in the United Kingdom through a UK Biodiversity Action Plan, and at the European level through its incorporation into strategic plans that included the target of 'significantly reducing the rate of biodiversity loss by 2010'. Also in 1992 (although not in force until 1998), a treaty on regional cooperation for the protection of the marine environment in the north-east Atlantic was also agreed. This treaty, known as the OSPAR Convention, was initially focused on pollution but was extended to include a commitment to an 'ecologically coherent network of marine protected areas by 2012' (OSPAR, 2010). At the European level, the Habitats Directive (European Commission, 1992; 92/43/EEC) was set up to protect species and habitats listed in its Annexes, primarily through the establishment of a network of sites (SACs) known as Natura 2000 (the network also includes Special Protection Areas designated under the Birds Directive).

Legislation in the 1990s, however, was still being developed in a piecemeal fashion and took a broadly sectoral approach (see Boyes and Elliott (2014) showing the 'patchwork' of legislation that has developed relating to UK marine environmental protection). For example in the fisheries sector, the Common Fisheries Policy (originally adopted in 1983, reformed 1992, 2002 and 2013; European Commission, 2013; EC No. 1380/2013) continued to be the key policy mechanism, while for marine industry sectors such as gas, oil and aggregates the requirement to provide Environmental Impact Assessments (EIAs) as a result of the 1997 EC Directive (European Commission, 1997; 97/11/EC) on the Assessment of the Effects of Certain Plans and Programmes on the Environment, was the most significant environmental legislation. By the start of the 21st century, an increasing focus on treating the marine environment in a more holistic manner was emerging, largely articulated through the 'ecosystem approach' (Farmer *et al.,* 2012). This led to a need for a more integrated approach to marine policy and resulting legislation. The most important developments in this respect were the European Water Framework Directive (WFD; European Commission, 2000; 2000/60/EC) and the MSFD (European Commission, 2008; 2008/56/EC). In the marine environment the WFD applies to transitional waters (estuaries) and coastal waters (up to 1 nm from territorial sea baselines, except for Scotland where it applies up to 3 nm from baselines), as well as inland surface waters (rivers and lakes) and groundwater. The aim of the WFD is to achieve Good Ecological and Chemical Status by 2015 and there is a large body of literature on the implementation of WFD with regard to marine biodiversity (see review by Hering *et al*., 2010). The MSFD complements the WFD in being applicable to inshore and offshore areas adjacent to the WFD area (although it overlaps with WFD in the coastal region between baselines and 1 or 3 nm). The MSFD outlines an ecosystem-based approach to the management of human activities that supports the sustainable use of marine goods and services. The overarching goal of the Directive is to achieve Good Environmental Status (GES) by 2020 across Europe's marine environment, and 11 high level descriptors of GES are outlined in the Directive itself. Although the MSFD does not identify what management measures should be taken to achieve GES, the Directive does require a programme of measures to be implemented and the establishment of marine protected areas.

One of the most significant developments in marine biodiversity policy in the UK is the growing focus on marine protected areas, particularly since 2009 (Figure 1). The first statutory Marine Nature Reserve in the UK was established in 1986; and, since this time, legislation relating to marine protected areas in the UK has proliferated with a number of designation mechanisms available (Figure 2). Together, these designations all contribute to the aim of establishing an ecologically coherent network of marine protected areas. While this network functions at the national level, it plays a wider international role as it helps deliver commitments under the Convention on Biological Diversity and the OSPAR Convention.

Although marine protected areas in the UK are supported by different legislative mechanisms, the sites all provide protection for marine biodiversity in a similar manner, with conservation objectives being set for those features listed (e.g. species, habitats or geological) as part of the marine protected area designation. The conservation objectives are a statement of the nature conservation aspirations for the designated features of a site, and these aspirations are expressed in terms of the condition that each feature should attain (Natural England, 2014). Favourable condition is the target condition for a feature to attain, in terms of its abundance, distribution and/or quality within a site (JNCC, 2003). As marine protected areas are such an important mechanism for protecting marine biodiversity (both nationally and globally), it is vital to address the question of whether current legislation can provide adequate protection in the face of climate change impacts.

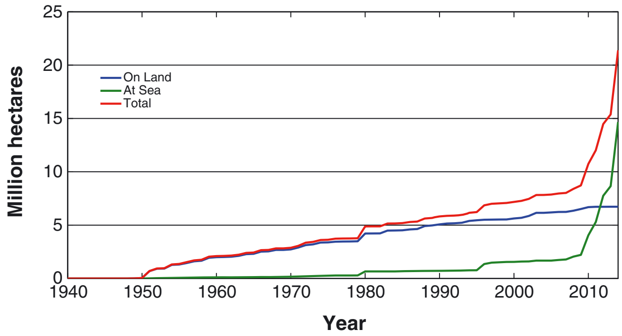

Figure 1. Extent of UK nationally and internationally important protected areas: on-land and at-sea, 1950 to 2014. This is reproduced from the JNCC website: http://jncc.defra.gov.uk/page-4241.

In addition to marine protected areas, there are a number of other spatial restrictions and measures in the UK which can contribute to conserving and improving the marine environment. For example, there are seasonal closures in the North Sea to protect spawning cod and in late 2014 there was a seasonal closure of the skates and rays fishery in the Eastern English Channel after landing figures showed the UK quota for skate and ray had been largely exhausted (MMO, 2014).

Finally, it is important to note marine biodiversity policy is constantly being updated with further revisions being made to high-level

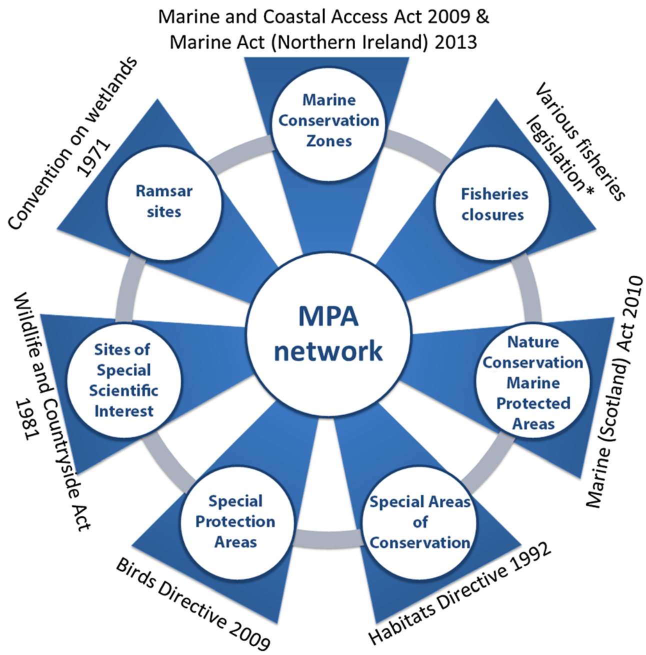

Figure 2. Overview of different types of marine protected areas and their associated designation mechanisms that are considered to contribute to a marine protected area network in the UK. More information on each of these designation mechanisms can be found on the Joint Nature Conservation Committees (JNCC) protected areas designation directory (JNCC, 2014). *Fisheries closures can include: national fishing prohibition orders such as those under the Sea Fish (Conservation) Act 1967 and the Inshore Fishing (Scotland) Act 1984; regulatory measures under the North-East Atlantic Fisheries Commission bylaws such as those under the Conservation of Habitats and Species Regulations 2010 and the Marine and Coastal Access Act, 2009; and technical measures regulations under the Common Fisheries Policy.

policy objectives as key dates come and go. For example, the 2011 EU Biodiversity Strategy (European Commission, 2011) now articulates both a 2020 and 2050 target. The former target is to halt the loss of biodiversity and the degradation of ecosystem services in the EU by 2020, and restore them in so far as feasible, while stepping up the EU contribution to averting global biodiversity loss. The 2050 vision is for EU biodiversity and the ecosystem services it provides – its natural capital – to be protected, valued and appropriately restored for biodiversity's intrinsic value and for their essential contribution to human wellbeing and economic prosperity, so that catastrophic changes caused by the loss of biodiversity are avoided.

The focus of this paper is, however, on the degree to which these various legislative mechanisms are suited to a climate-affected environment, rather than on broader policy goals and strategies, which are difficult to assess in terms of their implementation and effectiveness (Wood *et al.*, 2007).

KEY PHYSICAL CLIMATE CHANGE DRIVERS AFFECTING MARINE BIODIVERSITY AROUND THE UK

The following is a summary of the main climate change drivers affecting marine biodiversity which could potentially compromise the efficacy of marine biodiversity legislation. The summary is based on information collated during the production of the 2013 MCCIP report card (MCCIP, 2013) and updated where appropriate. Although the focus here is on the UK, many of the physical drivers of climate change described operate over spatial scales that extend well beyond the UK Exclusive Economic Zone and Continental Shelf. For example, impacts on marine biodiversity in the UK, such as temperature driven shifts in species distributions, are also being observed in many other countries (Parmesan and Yohe, 2003; Poloczanska *et al.*, 2013). In addition to changes in sea temperature, there is a wide range of other physical changes with implications for marine biodiversity. These drivers include changes in sea level, salinity, stratification, storms and waves, and ocean acidification. Climatic changes over the land also affect inputs into the sea. As such nutrient enrichment and pollution are also included in this summary.

Temperature

Sea temperature is the key physical climate change driver of relevance to marine biodiversity legislation, given its effects on the physiology and ecology of marine species (Hobday *et al.*, 2006; MCCIP, 2013; Poloczanska *et al.*, 2013). A time series of coastal sea surface temperature around the UK (Figure 3) shows a general warming trend over the past century, allowing for shorter term natural fluctuations.

Rapid warming between the mid-1980s and the mid-2000s (Rayner *et al.*, 2003; Mackenzie and Schiedek, 2007; Dye *et al.*, 2013a) was followed by slightly lower temperatures between 2007 and 2012 (Dye *et al.*, 2013a). Such short-term variability is consistent with decadal variability extending back over a century, and is expected to be a continued feature over the coming century against a backdrop of overall warming (Hawkins *et al.*, 2011; Hawkins, 2013).

Taking the next century as a whole, the UK Climate Projections 2009 (UKCP09) show an overall warming in all marine regions adjacent to the UK, of between 1.5 and about 4 °C. Southern regions are projected to warm faster than northern regions; while summer and autumn temperatures are projected to warm faster than winter and spring in the south of the region. It should be noted that these projections present just one physically plausible future using a medium emissions scenario (SRES A1B; Nakicenovic and Swart, 2000), derived from a single model, and therefore cannot provide a full assessment of uncertainty. New ensemble approaches are starting to take account of this uncertainty (Tinker *et al.*, 2015).

The changes in seawater temperature experienced over the last few decades have had numerous direct and indirect impacts on marine biodiversity. These impacts include changes across trophic levels and predator–prey relationships, from plankton to fish and birds; shifts in distributions of fish, plankton and intertidal species; implications for breeding success in sea birds; and phenological changes (e.g. timing of reproduction in fish and intertidal gastropods) (Heath *et al.,* 2012; MCCIP, 2012, 2013; Daunt and Mitchell, 2013; Edwards *et al.,* 2013; Mieszkowska *et al.*, 2013; Simpson *et al.*, 2013). Projections of sea temperature over nearer time horizons, rather than the end of 21st century are starting to be applied to marine ecosystem studies over wide spatial scales (e.g. bioclimate envelope models of fish distributions for the 2050s used by Jones *et al.* (2013)) and this will help facilitate forward planning for those responsible for implementing marine biodiversity legislation. These

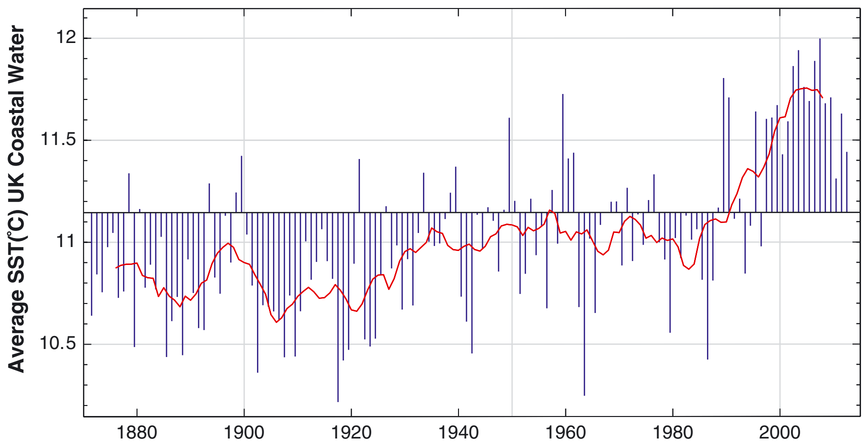

Figure 3. Time series of average SST in UK coastal waters. The blue bars show the annual values relative to the 1971–2000 average and the smoothed red line shows the 10-year running mean. Data are from the HadISST1.1 data set (Rayner *et al.*, 2003); figure courtesy of Sarah Hughes (Marine Scotland) in Dye, *et al.* (2013a) reproduced under the Open Government Licence v3.0- http://www.nationalarchives.gov.uk/doc/open-government-licence/version/3/.

new projections are for sea surface and bottom temperatures, as well as at multiple levels through the water column.

Sea level

Taking regional land movements into account, sea level around the UK coast has risen by 14 cm since 1901 (Horsburgh and Lowe, 2013). This 14 cm rise in sea level has significantly increased (as much as doubled) the risk of flooding since 1901 at many locations around the UK coastline (Donovan *et al*., 2013). Some shorter (decadal) time periods have shown rates of sea-level rise faster or slower than this century-long trend. It is not clear whether recent increases in the rate of sea-level rise (since 1990) are due to decadal variability or are part of a long-term trend (Horsburgh and Lowe, 2013).

The Intergovernmental Panel on Climate Change (IPCC) Fifth Assessment Report projects a global sea-level rise of between 29 and 82 cm by the end of this century, depending on greenhouse gas emissions (IPCC, 2013). While the most recent UK projections (UKCP09) are based on slightly lower figures derived from the IPCC Fourth Assessment Report, they are broadly consistent with these figures. Allowing for land movement, sea-level rise around the UK by the end of century is projected to be between 21 and 68 cm (Lowe *et al*., 2009). The same UK projections include an extreme, 'low probability, 'high++' sea-level rise' scenario closer to 2 m, based on previous high sea levels in the geological record. Effects of changing sea level are likely to include wetland and coastal plain flooding, coastal erosion, salinization of aquifers and soils, and a loss of habitats for fish, birds, and other wildlife and plants (IPCC 2007).

Salinity

Trends in salinity are highly variable, both spatially and temporally. The salinity of the upper ocean to the west and north of the UK has generally been increasing since a relatively fresh period in the 1970s. There is also evidence of a freshening of deep subsurface waters to the west (1970s to present) and north (1960s to 1990s) of the UK, but on the shelf there is no generally discernible long-term trend (Dye *et al.*, 2013b).

Future changes in salinity will be determined by the balance between saline oceanic influences linked to Atlantic circulation and freshwater contributions from polar melt, rivers and rainfall, and how these vary as the climate changes (Frost *et al.*, 2012). A general freshening trend over the next century is evident in UKCP09 projections of salinity (Lowe *et al.*, 2009), a signal which is more robust and stronger in new ensemble projections based on the same model (Tinker *et al*., unpublished data). Two further projections (Friocourt *et al.*, 2012; Gröger *et al.*, 2012), provide support for this freshening, but it should be noted that overall confidence in future changes in salinity is low (Dye *et al*., 2013b).

Changes in salinity can have an effect at every level of marine ecosystems including altering distribution and abundance, and even phenology and reproductive capabilities of some marine organisms; affecting planktonic and benthic microalgal community structure and function; the promotion of harmful blooms of cyanobacteria (Ojaveer and Kalejs, 2005; Paerl and Paul, 2012); and through to the establishment of non-native species (Cook *et al.*, 2013).

Stratification

Stratification occurs where 'layers' of warmer (or fresher) water sit above cooler (or saltier) water due to differences in density. Thermal stratification over the north-western European shelf seas is showing evidence of beginning slightly earlier in the year and there is also some suggestion of stratification strengthening beyond the normal inter-annual variability (Holt *et al*., 2012; Sharples *et al.*, 2013). Projections for the end of this century suggest that thermal stratification could become stronger and typically begin one week earlier in the year than at present, and end five to ten days later (Fernand, 2006; Lowe *et al.*, 2009; Sharples *et al.*, 2013). Stratification can also occur at the coast where fresh water coming off the land meets sea water, but as yet, there is no clear evidence of climate change affecting stratification due to salinity variations, and future projections are inconclusive (Sharples *et al.*, 2013).

Stratification in shelf seas affects biological growth. For instance, when stratification begins in spring the plankton trapped in the upper, well-lit water grow rapidly in the 'spring bloom'. This bloom is a short-lived feature, as the plankton rapidly consume the available nutrients in the surface water. Many other marine organisms time their breeding cycles to correspond with this sudden arrival of plankton (Sharples *et al.*, 2013). Changes in timing or strength of stratification can therefore have potential impacts on multiple trophic levels.

Storms and waves

The incidence of severe winds and wave heights in waters to the west and north of the UK and Ireland increased over the second half of the 20th century, although this could be part of long-term natural cycles operating over many decades (Alexander *et al.*, 2005; Wolf and Woolf, 2006; Nolan, Gillooly and Whelan, 2009). A general increase in wave heights has been observed in the north-east Atlantic since the end of the 19th century, but at a greater rate since the 1960s (Wang *et al.*, 2012; Woolf and Wolf, 2013).

Confidence in future wind and storm projections is very low, with some models suggesting that Europe might experience fewer major storms and others suggesting an increase (Woolf and Wolf, 2013). Climate change could affect wave heights by changing the intensity of storms, or their tracks; but, as there is very low confidence in projections of storms under future climate scenarios there is a correspondingly wide range in potential changes in wave height. Model projections (Lowe *et al.*, 2009) demonstrate this wide range in the potential changes for both seasonal means and annual extremes (changes in the winter mean wave height of between 35 cm decrease and 5 cm increase, and changes of the annual maxima of –1.5 m to +1 m are projected).

Any increase in turbidity, resulting from changes in storms and waves, will have a direct effect on light attenuation through the water column with potential effects on algae and other biota. Increased sediment loading in lakes has been shown to alter the ecological functioning and biotic assemblage structure, and reduce productivity and biodiversity (Donohue and Garcia Molinos, 2009). In a marine system any increased storminess and wave exposure resulting in changes to turbidity may similarly affect benthic ecosystems, seabed integrity and habitat classification, relevant to the MSFD and marine protected area legislation. Exposure to waves is known to be a determining factor in the presence and distribution of nutrients, pelagic ecology and plankton, and therefore classification of, marine habitats (Burrows, 2012; Woolf and Wolf, 2013).

Acidification and deoxygenation

As levels of atmospheric CO_2 rise, more is taken up by seawater, reducing its pH. Globally, the pH of surface water has decreased on average by 0.1 units since 1750 from 8.2 to 8.1 units, representing a 30% increase in hydrogen ion (H^+) concentration (Le Quéré *et al.*, 2009). This process of 'ocean acidification' is expected to continue in the future and by 2100, average ocean pH could fall as low as 7.8 units under the highest IPCC Fifth Assessment emission pathway (IPCC, 2013).

Warming seas are also likely to become less oxygenated because of the lower solubility of oxygen in warmer water and an increase in upper ocean stratification (UKMMAS, 2010). An analysis of historical data from ICES suggests seasonal oxygen reduction in the North Sea has increased over recent decades (Queste *et al.,* 2013).

Although the understanding of impacts of ocean acidification and deoxygenation are at an early stage, the potential impacts on the marine species and habitats being protected through marine protected areas and the implementation of MSFD could be profound (Williamson *et al.*, 2013). The chemistry of the ocean has a direct effect on the biology and the behaviour of many marine organisms particularly shell-forming species. While species more tolerant of these changes could benefit, the overall effect is expected to be deleterious to marine ecosystems and the services they provide, such as shellfish harvesting (Williamson *et al.*, 2013).

Precipitation, nutrients and pollution

As precipitation over the land changes in the future, the flow and quality of water moving from land to coastal and marine environments will also change. Since records began in 1766, there has been no significant change in mean annual rainfall across the UK, but the distribution and intensity has changed, with a tendency towards more heavy winter precipitation events and less extreme summer rainfall (UK Met Office, 2011).

By the end of this century, total annual UK rainfall is projected to be about the same, or slightly higher, but with drier summers, especially in the south and south west, and wetter winters, especially in the west of the UK (Lowe *et al.*, 2009). Extreme rainfall events are also generally projected to increase, by up to 30% in winter, spring, and autumn seasons (Fowler and Ekstrom, 2009).

The ‘Future Flows and Groundwater Levels project’ has modelled river flows and groundwater levels for the UK up to the 2080s, using inputs from UKCP09 under a medium emission scenario (British Geological Survey, 2012). The most marked changes are seen in summer, and in particular August where some model outputs suggest a decrease in flows of up to 80%.

Changes in flows from land to sea will have important impacts on the transfer of nutrients and microbial and chemical pollutants into the coastal and marine environment. Seasonal and regional changes in flows are likely to be significant, with implications for the protection of habitats and species, as well as compliance with EU directives (Sheahan *et al.*, 2013). For example, increased run-off from agricultural systems could increase the growth of harmful algal blooms (Baker-Austin *et al.*, 2013).

Overall, there is a large amount of evidence that climate change is having an impact on the marine environment. These impacts are predicted to continue, and in many cases become more severe, in the future. This is of fundamental importance in that it implies that marine environmental conditions as currently known, may continue to undergo significant changes in response to temperature and other drivers.

ANALYSIS OF MARINE BIODIVERSITY LEGISLATION

The key question for decision makers and marine managers is to what degree does the type of legislation so far discussed include provision for climate change impacts? The answer to this question determines whether current legislative mechanisms can effectively protect marine biodiversity in the face of climate change. In a best-case scenario, marine biodiversity legislation would be able to be used to ensure ongoing protection for marine biodiversity and the sustainable use of the marine environment, both of which are dynamic and subject to a wider range of climate impacts. In a worst-case scenario, major changes to marine biodiversity and the wider environment as a result of climate change could lead to current legislation having to be replaced with more flexible mechanisms or, if not, in a failure to prevent detrimental impacts on marine biodiversity. This analysis builds on two existing reviews, ‘Adapting to Climate Change in the Marine Environment (ACME)’ (Dye and Townhill, 2013) and ‘Towards a Marine Adaptation Action Plan (MACCAP)’ (Garnacho and Pinnegar, 2013). It further develops this work, however, by looking at both primary legislation and other mechanisms that sit beneath these policy frameworks and which therefore may allow for flexibility in implementation and approach. A summary of this analysis is provided in Table 1. More detailed explanatory text for each of the obligations described in Table 1, and the degree to which each has the capacity to account for climate change, is provided as supporting information.

Of the 21 obligations considered spanning nearly five decades (1966–2013) only three make specific reference to climate change, two of which are dedicated climate change acts, and none of those created before 2008 refer to climate change explicitly. However, nearly half of the obligations make reference to natural variability and environmental change and all include some formal review and reporting cycles as well as complementary

Table 1. Consideration of climate change in marine biodiversity legislation relevant to the UK

Obligations (in chronological order)	1. Does the text of the original legislation explicitly mention climate change?	2. Does the text of the original legislation include reference to natural variability or broader environmental change?	3a. Is there a review and reporting cycle? And how frequently?	3b. Are there mechanisms within the framework that might allow for impacts of climate change?	Notes
International Convention for the Conservation of the Atlantic Tuna (1966)	NO	NO	YES (2-8 years)	YES	Stock assessments, reviewed every 2-8 years, are based on data that implicitly include the effects of climate conditions; and have, for a number of years, explicity mentioned climate change.
EC Common Fisheries Policy (1970, 1983, 1987, 2002, 2013)	NO	NO	YES (annual)	YES	A number of mechanisms could allow adaptation to climate variability; e.g. regular update of fisheries agreements, multi-annual plans.
Ramsar Convention (1971)	NO	YES	YES (3 years)	YES	National implementation reports can introduce climate adaptation strategies.
CITES - Convention on International Trade in Endangered Species of Wild Fauna and Flora (1973)	NO	NO	YES	YES	Protected species listings can be amended with mechanisms in place for periodic reviews.
Bern Convention (1979)	NO	NO	YES	YES	Group of Experts on Biodiversity and Climate Change reviews the relevant effects of climate change and provides advice on developing adaptation and management policies.
Bonn Convention (Conservation of Migratory Species) (1979)	NO	NO	YES (3 years)	YES	Species listing decisions can draw on evidence on impacts of climate change.
EU Wild Birds Directive (1979; 2009)	NO	NO	YES (3 years)	YES	National implementation could accommodate for changes caused by environmental variability.
UK Wildlife and Countryside Act (1981 and subsequent amendments)	NO	NO	YES (5 years)	YES	Five-yearly review of protected wild animals and plants (Schedules 5 and 8) .
Convention for the conservation of salmon in the North Atlantic Ocean (1982)	NO	YES	YES (5 years)	YES	Implementation plans are prepared on a 5 year cycle with annual progress reporting. Can adapt management in response to environmental change.
Straddling Fish Stocks and Highly Migratory Fish Stocks Agreement (1982)	NO	YES	YES	YES	The agreement makes it clear that member states apply a precautionary approach in management of stocks that takes into account ’existing and

(*Continues*)

Table 1. (Continued)

Obligations (in chronological order)	1. Does the text of the original legislation explicitly mention climate change?	2. Does the text of the original legislation include reference to natural variability or broader environmental change?	3a. Is there a review and reporting cycle? And how frequently?	3b. Are there mechanisms within the framework that might allow for impacts of climate change?	Notes
					predicted' marine environmental conditions.
OSPAR Convention- The Convention for the Protection of the Marine Environment of the North-East Atlantic (1992)	NO	NO	YES (annual & 10 years)	YES	Climate change and ocean acidification are considered within the activities of all the OSPAR committees, but particularly by the Biodiversity Committee (BDC) and Environmental Impacts of Human Activities Committee (EIHA) which meet annually. Every 10 years the OSPAR Commission reports on the status of the maritime region and identifies priority actions including on climate change impacts, adaptation and mitigation.
EC Habitats Directive (1992)	NO	NO	YES (6 years)	YES	Specific guidance has been issued by the European Commission on the Directives's implematation with regard to climate change.
Convention on Biological Diversity (CBD; 1992, 1993)	NO	NO	YES (10 years)	YES	Actively addresses climate change providing framework under which national implementation can act. For example - the UK Biodiversity Action Plan provides the framework for addressing the linkage to climate change and CBD at the UK level.
EU Water Framework Directive (WFD) (2000)	NO	YES	YES	YES	The programme of measures within the required River Basin Management Plans are able to take account of the likely effects of climate change.
International Maritime Organisation - Ballast Water Convention (2004)	NO	NO	YES	YES	Periodic reviews through Regulation D-5 Review of Standards by the Organization. The Convention is not yet in force as it has yet to be ratified by enough parties. Climate change not directly relevant to the convention but its implementation would help mitigate any increased risk of the establishment of new species due to climate change.

(*Continues*)

Table 1. (Continued)

Obligations (in chronological order)	1. Does the text of the original legislation explicitly mention climate change?	2. Does the text of the original legislation include reference to natural variability or broader environmental change?	3a. Is there a review and reporting cycle? And how frequently?	3b. Are there mechanisms within the framework that might allow for impacts of climate change?	Notes
Marine Strategy Framework Directive (2008)	NO	YES	YES (6 years)	YES	Member state's marine strategies are developed and reviewed on a 6 yearly cycle. Implementation of the directive requires that environmental change be considered in a number of ways.
Climate Change Act (2008)	YES	YES	YES (5 years)	YES	A National Adaptation Programme (NAP) is required in response to each Climate Change Risk Assessment (CCRA).
Climate Change (Scotland) Act 2009	YES	YES	YES (5 years)	YES	Requirement for statutory adaptation programme to address the risks to Scotland identified in the CCRA for Scotland.
Marine and Coastal Access Act (2009); Marine Act (Northern Ireland), 2013	NO	YES	YES (6 years)	YES	"Marine Policy Statement" requires that marine plans and decisions consider how activities in the marine environment can adapt to the impacts of climate change.
Marine (Scotland) Act (2010)	YES	YES	YES (5 years)	YES	The national marine plan (2015) includes climate change objectives and policies. A review report after up to 5 years from publication of the National Marine Plan and then at least every 5 years.
Marine Act (Northern Ireland), 2013	NO	YES	YES (6 years)	YES	"Marine Policy Statement" requires that marine plans and decisions consider how activities in the marine environment can adapt to the impacts of climate change.

mechanisms where climate change impacts might be able to be considered. Even in the absence of a direct reference to climate change in the legislation's text, therefore, there are in many cases mechanisms to allow flexibility in their implementation which can address climate change.

DISCUSSION

Much of the early marine legislation reviewed in this paper does not explicitly consider natural climate variability or anthropogenic climate change. As this issue was receiving little attention in the scientific community at the time, it is hardly surprising that planned responses to climate change were not being considered. In fact, few early pieces of marine conservation legislation were created with any expectation that the species and habitats and environmental conditions they were set up to protect and manage would change to the degree now being observed. Other than the recent UK and Scottish Climate Change Acts (Climate Change Act, 2008; Climate Change Act (Scotland), 2009), only the Marine (Scotland) Act, 2010 mentions climate change explicitly. Even in the absence of direct references to climate change, however, there are in many cases secondary mechanisms allowing climate change to be considered. This may be because climate change can be addressed indirectly through consideration of natural environmental change and variation (Table 1, column 2). The Marine Strategy Framework Directive (MSFD) for example, has been written in the knowledge that marine systems are dynamic and includes adaptation and exception sections which require climate and environmental variability to be taken into account (the preamble setting up the Directive states that 'in view of the dynamic nature of marine ecosystems and their natural variability, and given that the pressures and impacts on them may vary with the evolvement of different patterns of human activity and the impact of climate change, it is essential to recognize that the determination of good environmental status may have to be adapted over time'). Any legislation that accommodates the knowledge that marine systems are inherently dynamic is more likely to enable successful implementation against a background of climate-driven variability. However, successful implementation not only requires a flexible and adaptive approach to management, but a consolidated and robust evidence-base to understand the changes that are happening. Determining what good environmental status looks like for marine biodiversity under different climate change scenarios requires knowledge about the physical drivers (e.g. temperature) and the likely responses from species and communities. Where these responses are being driven largely by climate change, specific biodiversity targets such as those relating to habitat and species abundance and distribution may have to be adjusted or GES may fail to be achieved for reasons over which a member state has no control (McQuatters-Gollop, 2012). It will also be important when choosing species-based indicators to consider the sensitivity and functional response of the species to direct and indirect effects of climate change (Rombouts *et al.*, 2013). The MSFD should allow for an adjustment in implementation, particularly as the main biodiversity descriptor (Descriptor 1) refers to maintaining biodiversity 'in line with prevailing physiographic, geographic and climatic conditions.' Reference to natural variability or broader environmental change in legislation is therefore useful where a strong evidence base exists on variability and the implications of this for marine biodiversity.

Another area where legislation can accommodate emerging knowledge on climate change impacts is in review cycles (Table 1, column 3a). This is where a cycle of reporting allows an update of status against agreed targets and objectives. An example of this is The Water Framework Directive (WFD), where implementation requires river basin management plans, which include estuaries and coasts, to be reviewed every 6 years. This would allow for programmes of measures within the plans to be adjusted in light of new information and understanding on climate impacts. Review cycles are also included in the Wildlife and Countryside Act (1981), with Schedules 5 and 8 of the Act (relating to animals and plants respectively) listing species to be given special protection from identified threats (e.g. specific human activities or disturbance). The schedules are reviewed every 5 years by the statutory nature conservation bodies, with the last review occurring in 2014. This review process allows the lists to be updated depending on conservation status of the species in question. Therefore, although the legislation was written with no mention of climate change, marine (and other) species can be added and afforded extra protection from other pressures if climate change is impacting their overall conservation status. Taking advantage of review cycles in this way is important as reducing pressures can also enhance marine resilience of marine ecosystems by decreasing their sensitivity to climate change (Perry *et al.*, 2010).

A more complex area of policy relates to complementary mechanisms (Table 1, column 5b). These mechanisms can range from the ability to include climate change considerations in developing marine plans or when creating bylaws (Marine and Coastal Access Act (2009); Marine Act (Northern Ireland), 2013) to the use of 'decisions' as found in the Convention on Biological Diversity (UN, 1992). Although no mention is made of climate change or environmental variability in the CBD itself, the 'decisions' made by the governing body of the convention (the Conference of Parties) can, and do, directly address climate change impacts on biodiversity. The resulting 'decisions' allow climate change to be accounted for in programmes of work such as the country-level biodiversity strategies (JNCC and Defra (on behalf of the Four Countries' Biodiversity Group), 2012). It is at this level of implementation therefore that information on climate impacts on marine biodiversity can most readily be taken into account.

The priority being given to developing and implementing legislation enabling the establishment of marine protected areas (e.g. the EC Habitats and Birds Directives) makes it a key focus in terms of how the legislation can be implemented in the face of climate change. Even on land where the rates of change in response to climate are often slower than in the marine environment (Burrows *et al.*, 2011; Poloczanska *et al.*, 2013), there is concern over whether protected areas have been established in a way that would provide ongoing protection for biodiversity (Gillingham *et al.*, 2015; Thomas and Gillingham, 2015). In the marine environment, factors such as water temperature, salinity, and stratification directly affect the habitats and species for which sites are designated, but climate-driven changes in these water-column parameters have, in general, not been considered as a central part of the site designation process or for ongoing management. Studies show that some features for which marine protected areas have been designated may have their distributions significantly affected by climate change leading to challenges in the ongoing management of the protected areas (Gormley *et al.*, 2015). Options need to be available so that where a marine protected area is designated for a single feature (i.e. species or habitat) and that feature is lost, the marine protected area may need to be abandoned and an alternative area may need to be designated to protect the feature elsewhere. At the very least, conservation objectives and targets for marine protected areas may need to be reviewed more regularly to ensure the best management at the site level in the face of climate change impacts (Barber, 2015).

In addition, marine protected area networks may offer an advantage over individual protected areas in a changing climate, if they are designed in such a way as to take future climate change into account. There are two reasons, however, why networks may not provide the advantage expected. First, although there is a thorough history in the literature of generic concepts for network design (e.g. larval dispersal and connectivity, Shanks *et al.*, (2003); focusing protection on species resilient to climate impacts, Day and Roff (2000)), the success of these design concepts in providing ecosystem resilience is yet to be determined through appropriate monitoring programmes of marine protected areas and networks. A global review of monitoring programmes concluded this to be a major gap in current literature, as only a few examples of monitoring being undertaken to assess network functioning could be found (Parry *et al.,* 2012). Second, the process by which marine protected areas are identified is influenced by a number of different interests, including socio-economic, and as a result networks may fail to meet their intended design objectives.

There is a developing understanding of the need to include consideration of climate change impacts across a range of national and international legislation, although the focus to date has largely been on legislation in relation to mitigation (see Nachmany *et al.* (2014) for a comprehensive review of climate change related legislation across 66 countries with all identified UK legislation being linked to mitigation). For the UK, a whole raft of legislation relevant to the marine environment now provides the framework for much of the conservation and protection for marine biodiversity, but its collective ability to provide flexible, adaptive and responsive mechanisms is yet to be tested when challenged with the dynamic and progressive changes that are expected in marine communities in response to climate change.

Beyond the UK, there is evidence that other countries are also grappling with the issue of how climate change impacts on marine biodiversity are accounted for in their policy frameworks. Seeney *et al.* (2013) reported that despite climate change being a key driver of biodiversity loss in the USA, consideration of climate science for statutorily driven species management, such as under the US Endangered Species Act (ESA), is at an early stage. For biodiversity at exceptionally high risk, such as that occurring on and around low-lying islands (with associated vulnerability to sea-level rise), an urgent need has been identified to incorporate climate change impacts into biodiversity research and management programmes (Courchamp *et al.*, 2014), yet this remains a challenge as there is currently no statutory duty to do this. A number of countries in Africa (Morocco, Mozambique, Tanzania) and Asia (Malaysia, Maldives, the Philippines, South Korea) include marine elements in their national adaptation plans (Nachmany *et al.*, 2014) but there is no evidence of marine biodiversity legislation being developed to account for climate change. Model predictions show significant geographical variation in climate impacts on marine biodiversity at a global scale so legislation, particularly that developed at a supra-national level, needs to be able to account for this lack of homogeneity of response.

Where legislation does not account for climate change, governments can respond by updating primary and secondary legislation, or adapt policy if the legislation so allows, to take account of the rapidly growing evidence base on climate change impacts. Adapting instruments of regulation to take account of marine climate change impacts, however, requires clear mechanisms and/or protocols allowing updates to instruments, targets, schedules or appendices that would be affected by changes in environmental conditions. Furthermore, international agreements are often written without a clear definition of baselines and thresholds, making it difficult to assess the need for an update to incorporate climate change risk. This is an area where science could inform the implementation of legislation by helping address the notoriously difficult issue of establishing baselines. Defining thresholds/targets for MSFD, WFD and other marine legislation, for example, would benefit from being able to use non-impacted reference areas (sometimes referred to as 'pristine') or historical reference conditions, but this approach is complicated by climate change impacts both now and over long timescales respectively (Borja *et al.*, 2012). Only where high-quality, long-term datasets are available can the climate change impacts be accounted for in establishing baselines and targets (McQuatters-Gollop, 2012). In addition, the long time frames over which some of the more severe impacts of climate change on marine biodiversity are predicted to occur may lead to a lack of urgency in taking appropriate action. Ocean acidification impacts on deep cold-water corals, for example, may not be fully realized for decades based on current models but that does not mean that the focus should currently only be on reducing other pressures. It is known that they are ultimately vulnerable so legislation allowing a degree of adaptation (e.g. changing boundaries of marine protected areas) should be considered sooner rather than waiting for the impacts to occur. In other cases, where climate impacts are already being observed (e.g. mobile species such as fish), the need to make sure policy updates account for this is more urgent. The advantages of having biodiversity legislation suitable for climate-impacted ecosystems go well beyond the marine environment. The terrestrial and freshwater environments are often covered by the same legislation as the marine environment (e.g. CBD, Habitats Directive) so what is true for marine in terms of the need to address the lack of a focus on climate change in some legislation is also true for the terrestrial and freshwater environment.

The reliance on legislation and, in particular, that relating to marine protected areas as the main tool for marine biodiversity conservation, means there is an ongoing requirement to ensure implementation is not being compromised by climate change. Although there is flexibility in some marine biodiversity legislation to allow adaptation to the impacts of climate change, there is little evidence that these opportunities are yet being realized. Furthermore, more consideration needs to be given to current and future impacts on marine biodiversity when new legislative mechanisms are developed or existing legislation is updated.

In order for policymakers to be able to consider climate change in developing new legislation, or in amending or implementing current legislation, there needs to be an effective information flow between the science and policy communities. For example, it is important that policymakers are able to utilize the increasing understanding of marine climate change drivers. Specifically, work in the marine science community to improve the accuracy and reliability of predictive models continues to develop rapidly (Fennel and Neumann, 2014). Investigations into the use of marine modelling to inform management and policy issues are receiving increased attention (Fulton *et al.*, 2011; Coll and Libralato, 2012; Fulton *et al.*, 2015). Velocity of Climate Change (VoCC) analysis for example (Poloczanska *et al.*, 2013; Molinos *et al.*, 2015) provides a simple measure of likely changes, along with speed and direction, in parameters such as sea surface temperature. This can be used to show where climate change may have the greatest impact, information that can then be used when implementing spatially specific policy (e.g. marine protected areas, spatial plans). Recent work by Fulton *et al.* (2015) on modelling and marine protected areas addresses the use of models when climate-related ecosystem restructuring and range shifts compromise the objectives of marine protected areas, as discussed in this paper and recent reports (MCCIP, 2015). Models applied to marine reserves in Australia showed some of the reserves designed to protect specific vulnerable habitats retained their value despite being subject to the wider impacts of climate change (Fulton *et al.*, 2015). Modelling can also be used to inform other elements of biodiversity legislation beyond those just related to spatial management. Annex IV of the EC Habitats Directive contains a number of marine species for which a system of strict protection has to be established (at the national level there are also species requiring protection in Schedule V of the Wildlife and Countryside Act, 1981). Bioclimate envelope models and similar empirical approaches can be used in this case to see how climate change might impact specific species both in terms of distribution but also for measures of condition such as population abundance.

Better use of science, and specifically models, is not the only way that climate change considerations can be accounted for in developing and implementing marine legislation (there are also policy considerations, such as use of evidence) but this would go some way to addressing any potential implementation gap. Among some conservation scientists, there is little appetite for revisiting legislation, and flexibility around issues such as amending annexes is seen as a potentially negative approach, detracting from the need to get on with implementation (Maes *et al.*, 2013). This analysis has, however, shown that enough flexibility exists to move forward with implementing marine biodiversity legislation even if there are some areas (e.g. flexibility of marine protected area designations) that may present challenges in the future.

ACKNOWLEDGEMENTS

This paper was initiated through the UK Marine Climate Change Impacts Partnership (MCCIP). This review has drawn on material published under the Defra funded projects ‘Towards a Marine Adaptation Action Plan (MACCAP: ME5417) and ‘Adapting to Climate Change in the Marine Environment’ (ACME: E5102). We would also like to thank individuals within Defra and Marine Scotland for reviewing the technical aspects of legislation included in this review. Sanderson was supported by the The Marine Alliance for Science and Technology for Scotland pooling initiative (SFC grant HR09011).

REFERENCES

Alexander LV, Tett SFB, Jonsson T. 2005. Recent observed changes in severe storms over the United Kingdom and Iceland. *Geophysical Research Letters* **32**: L13704.

Baker-Austin C, Campos CJA, Turner A, Higman WA, Lees D. 2013. Impacts of climate change on human health. *MCCIP Science Review* **2013**: 257–262.

Barber R. 2015. *MMO Climate Change Adaptation Report*, Marine Management Organisation: Newcastle.

Bell S, McGillivray D, Perdersen OW. 2013. *Environmental Law*, Oxford University Press: Oxford.

Borja Á, Dauer DM, Grémare A. 2012. The importance of setting targets and reference conditions in assessing marine ecosystem quality. *Ecological Indicators* **12**: 1–7.

Boyes SJ, Elliott M. 2014. Marine legislation – the ultimate 'horrendogram': International law, European directives & national implementation. *Marine Pollution Bulletin* **86**: 39–47.

British Geological Survey. 2012. Future flows and groundwater levels: projections for the 21st century. http://www.bgs.ac.uk/research/groundwater/change/FutureFlows/home.html [10 April 2014].

Burrows MT. 2012. Influences of wave fetch, tidal flow and ocean colour on subtidal rock communities. *Marine Ecological Progress Series* **445**: 193–207.

Burrows MT, Schoeman DS, Buckley LB, Moore P, Poloczanska ES, Brander KM, Brown C, Bruno JF, Duarte CM, Halpern BS, *et al*. 2011. The pace of shifting climate in marine and terrestrial ecosystems. *Science* **334**: 652–655.

Callaway R, Shinn AP, Grenfell SE, Bron JE, Burnell G, Cook EJ, Crumlish M, Culloty S, Davidson K, Ellis RP, *et al*. 2012. Review of climate change impacts on marine aquaculture in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems* **22**: 337–367.

Cheung WWL, Pinnegar JK, Merino G, Jones MC, Barange M. 2012. Review of climate change impacts on marine fisheries in the UK and Ireland. *Aquatic Conservation: Marine and Freshwater Ecosystems* **22**: 368–388.

Climate Change Act. 2008. (c.27)., The Stationery Office: London.

Climate Change Act (Scotland). 2009. The Stationery Office: London.

Coll M, Libralato S. 2012. Contributions of food web modelling to the ecosystem approach to marine resource management in the Mediterranean Sea. *Fish and Fisheries* **13**: 60–88.

Cook EJ, Jenkins S, Maggs C, Minchin D, Mineur F, Nall C, Sewell J. 2013. Impacts of climate change on non-native species. *MCCIP Science Review* **2013**: 155–166.

Courchamp F, Hoffmann BD, Russell JC, Leclerc C, Bellard C. 2014. Climate change, sea-level rise, and conservation: keeping island biodiversity afloat. *Trends in Ecology & Evolution* **29**: 127–130.

Daunt F, Mitchell I. 2013. Impacts of climate change on seabirds. *MCCIP Science Review* **2013**: 125–133.

Day J, Roff JC. 2000. *Planning for Representative Marine Protected Areas: A Framework for Canada's Oceans*, Report prepared for World Wildlife Fund Canada: Toronto.

Donohue I, Garcia Molinos J. 2009. Impacts of increased sediment loads on the ecology of lakes. *Biological Reviews* **84**: 517–531.

Donovan B, Horsburgh K, Ball T, Westbrook G. 2013. Impacts of climate change on coastal flooding. *MCCIP Science Review* **2013**: 211–218.

Dye SR, Holliday NP, Hughes SL, Inall M, Kennington K, Smyth T, Tinker J, Andres O, Beszczynska-Möller A. 2013b. Impacts of climate change on salinity. *MCCIP Science Review* **2013**: 60–66.

Dye SR, Hughes SL, Tinker J, Berry DI, Holliday NP, Kent EC, Kennington K, Inall M, Smyth T, Nolan G, *et al*. 2013a. Impacts of climate change on temperature (air and sea). *MCCIP Science Review* **2013**: 1–12.

Dye SR, Townhill B. 2013. Adapting to climate change in the Marine Environment (ACME). Defra project ME5102 Final Report. http://randd.defra.gov.uk [10 December 2014]

Edwards M, Bresnan E, Cook K, Heath M, Helaouet P, Lynam C, Raine R, Widdicombe C. 2013. Impacts of climate change on plankton. *MCCIP Science Review* **2013**: 98–112.

European Commission. 1992. Council Directive 92/43/EEC of 21 May 1992 on the conservation of natural habitats and of wild fauna and flora. *Official Journal of the European Union* **L206**: 7–50.

European Commission. 1997. Council Directive 97/11/EC of 3 March 1997 amending Directive 85/337/EEC on the assessment of the effects of certain public and private projects on the environment. *Official Journal of the European Union* **L73**: 5–15.

European Commission. 2000. Directive 2000/60/EC of the European Parliament and of the Council of 23 October 2000 establishing a framework for Community action in the field of water policy. *Official Journal of the European Union* **L327**: 1–73.

European Commission. 2008. Directive 2008/56/EC of the European Parliament and of the Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive). *Official Journal of the European Union* **L164**: 19–40.

European Commission. 2009. Council Directive 2009/147/EC on the conservation of wild birds (codified version). *Official Journal of the European Union* **L20**: 7–25.

European Commission. 2011. Our life insurance, our natural capital: an EU Biodiversity Strategy to 2020, COM (2011) 244 final. http://eur-lex.europa.eu/LexUriServ/LexUriServ.do?uri=COM:2011:0244:FIN:EN:PDF [10th December 2014].

European Commission. 2013. Council Regulation (EC) No 1380/2013 Regulation (EU) No 1380/2013 of the European Parliament and of the Council of 11 December 2013 on the Common Fisheries Policy, amending Council Regulations (EC) No 1954/2003 and (EC) No 1224/2009 and repealing Council Regulations (EC) No 2371/2002 and (EC) No 639/2004 and Council Decision 2004/585/EC. *Official Journal of the European Union* **L354**: 22–63.

FAO. 2015. http://www.fao.org/wairdocs/ilri/x5459e/x5459e04.htm [14 June 2015]

Farmer A, Mee L, Langmead O, Cooper P, Kannen A, Kershaw P, Cherrier V. 2012. The Ecosystem Approach in Marine Management. EU FP7 KNOWSEAS Project. ISBN 0-9529089-5-6.

Fennel W, Neumann T. 2014. *Introduction to the Modelling of Marine Ecosystems*: (with MATLAB programs on accompanying CD-ROM), **72**Elsevier.

Fernand LJ. 2006. Final Report of Consensus on Pathways in European Shelf Seas. Defra Contract No. AE1225. http://randd.defra.gov.uk/Document.aspx?Document=AE1225_4777_FRP.pdf [10 December 2014]

Fowler HJ, Ekstrom M. 2009. Multi-model ensemble estimates of climate change impacts on UK seasonal precipitation extremes. *International Journal of Climatology* **29**: 385–416.

Friocourt YF, Skogen MD, Stolte W, Albretsen J. 2012. Marine downscaling of a future climate scenario in the North Sea and possible effects on dinoflagellate harmful algal blooms. *Food Additives & Contaminants: Part A* **29**: 1630–1646.

Frost M, Baxter JM, Buckley PJ, Cox M, Dye SR, Withers Harvey N. 2012. Impacts of climate change on fish, fisheries and aquaculture. *Aquatic Conservation: Marine and Freshwater Ecosystems* **22**: 331–336.

Frost MT, Hawkins SJ. 2007. UK marine policy and long-term marine monitoring programmes. In *The Evaluation of Time Series: their Scientific Value and Contribution to Policy Needs.* Frost MT, Jefferson R, Hawkins SJ (eds). *Occasional Publication of the Marine Biological Association of the United Kingdom* **22**: 94.

Fulton EA, Bax NJ, Bustamante RH, Dambacher JM, Dichmont C, Dunstan PK, Smith DC. 2015. Modelling marine protected areas: insights and hurdles. *Philosophical Transactions of the Royal Society B* **370**(1681): 20140278.

Fulton EA, Link JS, Kaplan IC, Savina-Rolland M, Johnson P, Ainsworth C, Smith DC. 2011. Lessons in modelling and management of marine ecosystems: the Atlantis experience. *Fish and Fisheries* **12**: 171–188.

Garnacho E, Pinnegar J. 2013. Towards a Marine Climate Change Action Plan. Defra project ME5417 and Cefas Contract C5397 Final Report. Cefas: Lowestoft. http://randd.defra.gov.uk [10 December 2014].

Gillingham PK, Bradbury RB, Roy DB, Anderson BJ, Baxter JM, Bourn NAD, Crick HQP, Findon RA, Fox R, Franco A, *et al*. 2015. The effectiveness of protected areas in the conservation of species with changing geographical ranges. *Biological Journal of the Linnean Society* **115**: 707–717.

Gormley KSG, Hull AD, Porter JS, Bell MC, Sanderson WG. 2015. Adaptive management, international co-operation and planning for marine conservation hotspots in a changing climate. *Marine Policy* **53**: 54–66.

Gröger M, Maier-Reimer E, Mikolajewicz U, Moll A, Sein D. 2012. North-west European shelf under climate warming: implications for open ocean – shelf exchange, primary production, and carbon absorption. *Biogeosciences Discussion* **9**: 16625–16662.

Hawkins E. 2013. Recent slowdown in global surface temperature rise. http://www.climate-lab-book.ac.uk/2013/recent-slowdown/#more-1520 [25 July 2014].

Hawkins E, Robson J, Sutton R, Smith D, Keenlyside N. 2011. Evaluating the potential for statistical decadal predictions of sea surface temperatures with a perfect model approach. *Climate Dynamics* **37**: 2495–2509.

Heath MR, Neat FC, Pinnegar JK, Reid DG, Sims DW, Wright PJ. 2012. Review of climate change impacts on marine fish and shellfish around the UK and Ireland. *Aquatic Conservation: Marine Freshwater Ecosystems* **22**: 337–367.

Hering D, Borja A, Carstensen J, Carvalho L, Elliott M, Feld CK, Heiskanen A-S, Johnson RK, Moe J, Pont D, *et al*. 2010. The European Water Framework Directive at the age of 10: a critical review of the achievements with recommendations for the future. *Science of the Total Environment* **408**: 4007–4019.

Hinchen H. 2014a. Review of marine biodiversity assessment obligations in the UK. Part I: A summary of the marine biodiversity assessment obligations stipulated within national and international legislative and policy instruments. JNCC Report 497. Joint Nature Conservation Committee, Peterborough.

Hinchen H, 2014b. Review of marine biodiversity assessment obligations in the UK. Part II: Identifying similarities and differences between marine biodiversity assessment obligations. JNCC Report 497. Joint Nature Conservation Committee, Peterborough.

Hiscock K (ed.). 1996. *Marine Nature Conservation Review: Rationale and Methods*. Coasts and seas of the United Kingdom. MNCR series. Joint Nature Conservation Committee: Peterborough.

Hobday AJ, Okey TA, Poloczanska ES, Kunz TJ, Richardson AJ. 2006. Impacts of climate change on Australian marine life. http://pandora.nla.gov.au/pan/102841/20090717-1556/www.climatechange.gov.au/impacts/publications/marinelife.html [10 April 2014].

Holt J, Hughes S, Hopkins J, Wakelin S, Holliday NP, Dye S, González-Pola C, Hjøllo SS, Mork KA, Nolan G, *et al*. 2012. Multi-decadal variability and trends in the temperature of the northwest European continental shelf: A model-data synthesis. *Progress in Oceanography* **106**: 96–117.

Horsburgh K, Lowe J. 2013. Impacts of climate change on sea level. *MCCIP Science Review* **2013**: 27–33.

IPCC (Intergovernmental Panel for Climate Change). 2007. Summary for Policymakers. In *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, Solomon S, Qin D, Manning M, Chen Z, Marquis M, Averyt KB, Tignor M, Miller HL (eds). Cambridge University Press: Cambridge and New York.

IPCC (Intergovernmental Panel for Climate Change). 2013. Summary for Policymakers. In *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 TF, Qin D, Plattner GK, Tignor M, Allen SK, Boschung J, Nauels A, Xia Y, Bex V, Midgley PM (eds). Cambridge University Press: Cambridge, and New York.

JNCC. 2014. Joint Nature Conservation Committees (JNCC) protected areas designation directory. http://jncc.defra.gov.uk/page-1527 [10 December 2014]

JNCC (Joint Nature Conservation Committee). 2003. Guidance for Common Standards Monitoring Introduction Text. http://jncc.defra.gov.uk/page-2201 [18 November 2014].

JNCC and Defra (on behalf of the Four Countries' Biodiversity Group). 2012. UK Post-2010 Biodiversity Framework. http://jncc.defra.gov.uk/page-6189 [18 November 2014].

Jones MC, Dye SR, Fernandes JA, Frölicher TL, Pinnegar JK, Warren R, Cheung WWL. 2013. Predicting the Impact of Climate Change on Threatened Species in UK Waters. *PLoS ONE* **8**(1): e54216. DOI:10.1371/journal.pone.0054216.

Le Quéré C, Raupach MR, Canadell JG, Marland G, Bopp L, Ciais P, Conway TJ, Doney SC, Feely R, Foster P, *et al*. 2009. Trends in the sources and sinks of carbon dioxide. *Nature Geoscience* **2**: 831–836.

Lowe JA, Howard TP, Pardaens A, Tinker J, Holt J, Wakelin S, Milne G, Leake J, Wolf J, Horsburgh K, *et al*. 2009. *UK Climate Projections Science Report: Marine and Coastal Projections*, Met Office Hadley Centre: Exeter.

MacKenzie BR, Schiedek D. 2007. Daily ocean monitoring since the 1860s shows record warming of northern European seas. *Global Change Biology* **13**: 1335–1347.

Maes D, Collins S, Munguira ML, Šašić M, Settele J, van Swaay C, Verovnik R, Warren M, Wiemers M, Wynhoff I. 2013. Not the right time to amend the annexes of the European Habitats Directive. *Conservation Letters* **6**: 468–469.

Marine (Scotland) Act. 2010 www.legislation.gov.uk/asp/2010/5 [10 December 2014]

Marine Act (Northern Ireland). 2013. www.legislation.gov.uk/nia/2013/10 [10 December 2014]

Marine and Coastal Access Act. 2009. www.legislation.gov.uk/ukpga/2009/23 [10 December 2014]

MCCIP. 2006. Marine Climate Change Impacts Annual Report Card 2006. Buckley PJ, Dye SR, Baxter JM (eds). Summary Report, MCCIP: Lowestoft.

MCCIP. 2008. Marine Climate Change Impacts Annual Report Card 2007-2008. Baxter JM, Buckley PJ, Wallace CJ (eds). Summary Report, MCCIP: Lowestoft.

MCCIP. 2009. Marine Climate Change Ecosystem Linkages Report Card 2009. Baxter JM, Buckley PJ, Frost MT (eds). Summary Report, MCCIP: Lowestoft.

MCCIP. 2010. Marine Climate Change Impacts Annual Report Card 2010-2011. Baxter JM, Buckley PJ, Wallace CJ (eds). Summary Report, MCCIP: Lowestoft.

MCCIP. 2012. Marine Climate Change Impacts on Fish, Fisheries and Aquaculture. Frost, MT, Baxter JM, Buckley PJ, Cox M, Dye SR, Withers Harvey N (eds). Summary Report, MCCIP: Lowestoft.

MCCIP. 2013. *Marine Climate Change Impacts Report Card 2013*. Frost, MT, Baxter, JM, Bayliss-Brown GA, Buckley PJ, Cox M, Withers Harvey N (eds). Summary Report, MCCIP: Lowestoft.

MCCIP. 2015. *Marine climate change impacts: implications for the implementation of marine biodiversity legislation*. Frost M, Bayliss-Brown G, Buckley P, Cox M, Stoker B and Withers Harvey N (eds). Summary Report, MCCIP, Lowestoft.

McQuatters-Gollop A. 2012. Challenges for implementing the Marine Strategy Framework Directive in a climate of macroecological change. *Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences* **370**: 5636–5655.

Mieszkowska N, Firth L, Bentley M. 2013. Impacts of climate change on intertidal habitats. *MCCIP Science Review* **2013**: 180–192.

MMO. 2014. Marine Management Organisation. Fisheries closures explained. https://www.gov.uk/government/news/fisheries-closures-explained. [May 29 2015].

Molinos JC, Halpern BS, Schoeman DS, Brown CJ, Kiessling W, Moore PJ, Pandolfi JM, Poloczanska ES, Richardson AJ, Burrows MT. 2015. Climate velocity and the future global redistribution of marine biodiversity. *Nature Climate Change* **6**: 83–88. DOI:10.1038/nclimate2769.

Möllmann C, Conversi A, Edwands M. 2011. Comparative analysis of European wide marine ecosystem shifts: a large-scale approach for developing the basis for ecosystem-based management. *Biology Letters* **7**: 484–486.

Nachmany M, Fankhauser S, Townshend T, Collins M, Landesman T, Matthews A, Pavese C, Rietig K, Schleifer P, Setzer J. 2014. *The GLOBE Climate Legislation Study: A Review of Climate Change Legislation in 66 Countries*, 4th edn.GLOBE International and the Grantham Research Institute, London School of Economics: London.

Nakicenovic N, Swart R. 2000. Special Report on Emissions Scenarios. A Special Report of Working Group III of the Intergovernmental Panel on Climate Change. Cambridge University Press: Cambridge and New York.

Natural England. 2014. Conservation Advice for Marine Protected Areas. http://publications.naturalengland.org.uk/file/6296485146656768 [18 November 2014].

NCC and NERC. 1979. Nature conservation in the marine environment. Report of the NCC/NERC joint working party on marine wildlife conservation. Nature Conservancy Council: London.

NERC. 1973. *Marine wildlife conservation: an assessment of evidence of a threat to marine wildlife and the need for conservation measures*, Publication Series 'B', No. 5, Natural Environment Research Council: London.

NERC and NC. 1969. Conservation Policy in shallow seas. Joint action meeting with the committee for Wales, Scottish Committee, the Scientific Policy Committee. Committee for England.

Nolan G, Gillooly M, Whelan K. 2009. *Irish Ocean Climate and Ecosytem Status Report 2009*, Galway: Marine Institute.

Ojaveer E, Kalejs M. 2005. The impact of climate change on the adaptation of marine fish in the Baltic Sea. *ICES Journal of Marine Science* **62**: 492–500.

OSPAR. 2010. OSPAR Convention for the Protection of the Marine Environment of the Northeast Atlantic, Meeting of the OSPAR Commission, Bremen, 23–27 June 2003. OSPAR Recommendation 2003/3 adopted by OSPAR 2003 (OSPAR 03/17/1, Annex 9), amended by OSPAR Recommendation 2010/2 (OSPAR 10/23/1, Annex 7).

Paerl HW, Paul VJ. 2012. Climate change: Links to global expansion of harmful cyanobacteria. *Water Research* **46**: 1349–1363.

Parmesan C, Burrows MT, Duarte CM, Poloczanska ES, Richardson AJ, Schoeman DS, Singer MC. 2013. Beyond climate change attribution in conservation and ecological research. *Ecology Letters* **16**: 58–71.

Parmesan C, Yohe G. 2003. A globally coherent fingerprint of climate change impacts across natural systems. *Nature* **421**: 37–42.

Parry M, Tierney M, Wood L, Stanwell-Smith D, Northen K, Abdulla A, Corrigan C, Gassner P, Fletcher L. 2012. Review of international Marine Protected Area seabed monitoring and assessment of 'good practice' to inform application within UK waters. JNCC Report No. 460, Peterborough. ISSN 0963 8091.

Perry R, Cury P, Brander K, Jenning S, Möllmanne C, Planquef B. 2010. Sensitivity of marine systems to climate and fishing: Concepts, issues and management responses. *Journal of Marine Systems* **79**: 427–435.

Poloczanska ES, Brown CJ, Sydeman WJ, Kiessling W, Schoeman DS, Moore PJ, Brander K, Bruno JF, Buckley LB, Burrows MT, *et al*. 2013. Global imprint of climate change on marine life. *Nature Climate Change* **3**: 919–925.

Queste BY, Fernand L, Jickells TD, Heywood KJ. 2013. Spatial extent and historical context of North Sea oxygen depletion in August 2010. *Biogeochemistry* **113**: 53–68.

Rayner NA, Parker DE, Horton EB, Folland CK, Alexander LV, Rowell DP, Kent EC, Kaplan A. 2003. Global analyses of sea surface temperature, sea ice, and night marine air temperature since the late nineteenth century. *Journal of Geophysical Research: Atmospheres (1984–2012)* **108**(D14): 4407. DOI:10.1029/2002JD002670.

Rombouts I, Beaugrand G, Fizzala X, Gaill F, Greenstreet SPR, Lamare S, Le Loc'h F, McQuatters-Gollop A, Mialet

B, Niquil N, *et al*. 2013. Food web indicators under the Marine Strategy Framework Directive: From complexity to simplicity? *Ecological Indicators* **29**: 246–254.

Seeney EE, Rowland MJ, Lowery RA, Griffis RB, McClure MM. 2013. Climate change, marine environments, and the US Endangered species act. *Conservation Biology* **27**: 1138–1146.

Shanks AL, Grantham BA, Carr MH. 2003. Propagule dispersal distance and the size and spacing of marine reserves. *Ecological Applications* **13**: S159–S169.

Sharples J, Holt J, Dye SR. 2013. Impacts of climate change on shelf sea stratification. *MCCIP Science Review* **2013**: 67–70.

Sheahan D, Maud J, Wither A, Moffat C, Engelke C. 2013. Impacts of climate change on pollution (estuarine and coastal). *MCCIP Science Review* **2013**: 244–251.

Simpson SD, Blanchard JL, Genner MJ. 2013. Impacts of climate change on fish. *MCCIP Science Review* **2013**: 113–124.

Thomas CD, Gillingham PK. 2015. The performance of protected areas for biodiversity under climate change. *Biological Journal of the Linnean Society* **115**: 718–730.

Tinker J, Lowe J, Holt J, Pardaens A, Barciela R. unpublished data. The uncertainty in climate projections for the 21st century NW European shelf seas.

Tinker J, Lowe J, Holt J, Pardaens A, Wiltshire A. 2011. Validation of an ensemble modelling system for climate projections for the northwest European shelf seas. *Progress In Oceanography*.

UK Met Office. 2011. Climate: observations, projections and impacts. http://www.metoffice.gov.uk/media/pdf/t/r/UK.pdf [13 February 2014].

UKMMAS. 2010. *Charting Progress 2 Feeder Report: Ocean Processes*, Department for Environment Food and Rural Affairs on behalf of UKMMAS.

United Nations. 1992. *Convention on Biological Diversity*. United Nations: New York.

Wang XL, Feng Y, Swail VR. 2012. North Atlantic wave height trends as reconstructed from the 20th century reanalysis. *Geophysical Research Letters* **39**: L18705.

Wildlife and Countryside Act. 1981 (c.69). The Stationery Office: London.

Williamson P, Turley C, Brownlee C, Findlay HS, Ridgwell A, Schmidt DN, Schroeder DC, Blackford J, Tyrell T, Pinnegar JK. 2013. Impacts of ocean acidification. *MCCIP Science Review* **2013**: 34–48.

Wolf J, Woolf DK. 2006. Waves and climate change in the north-east Atlantic. *Geophysical Research Letters* **33**: L06604.

Wood LJ, Fisha L, Laughrena J, Pauly D. 2007. Assessing progress towards global marine protection targets: shortfalls in information and action. *Oryx* **42**: 340–351.

Woolf D, Wolf J. 2013. Impacts of climate change on storms and waves. *MCCIP Science Review* **2013**: 20–26.

Supporting Information

Additional supporting information may be found in the online version of this article at the publisher's web site.