

# Climate Change Impacts on Marine Mammals around the UK and Ireland

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## KEY FACTS

### What is happening

- The main impacts of climate change on marine mammals continue to be geographic range shifts, reduction in suitable habitats, food web alterations and increased prevalence of disease.
- Evidence for range shifts is increasing, with an apparent northward shift in some warmer water cetacean species around the UK. For example, pilot whale populations in the northwest Atlantic have shifted northward at a faster rate than expected, more than three times the rate of their preferred prey species.
- Increasing sea surface temperatures and marine mammal range shifts are resulting in novel interactions and increased predation risk and competition for species.
- New evidence continues to support understanding that changes in summer algal blooms and zooplankton affect important prey species such as sandeels.

### What could happen in the future

- Species closely tied to their breeding grounds, are more likely to be affected by changes in sea surface temperature as this will impact both habitat availability and the breeding behaviours associated with that habitat.
- Risks to marine mammals from disease and thermal stress may increase.
- Changing environmental conditions may affect when marine mammals breed, particularly those species that build up energy stores beforehand.
- Marine mammals face an increase in the cumulative impacts from climate change and other increasing pressures such as marine renewable expansion.

## SUPPORTING EVIDENCE

### Introduction

UK waters are home to several species of marine mammals. The most common are grey seal, harbour seal, bottlenose dolphin, harbour porpoise, minke whale, short-beaked common dolphin, Atlantic white-sided dolphin, white-beaked dolphin, Risso's dolphin, killer whale, long-finned pilot whale,

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fin whale and sperm whale. However, vagrant species also include humpback whale, blue whale, sei whale, northern bottlenose whale, several species of beaked whale, striped dolphin, hooded seal and bearded seal. Over the past several decades, human activities have caused unprecedented environmental changes in the marine environment which may be impacting these species both within UK waters and globally. The UK is well-placed to see these changes due to its position between the warmer subtropical waters and colder Arctic waters that places the UK at the edge of thermal tolerances for both cold and warm water species (Williamson *et al.*, 2021; Sonnewald and Lguensat, 2021). Around the UK, sea temperatures are rising, with the most significant increases occurring around northern Scotland and most of the North Sea (Tinker and Howes, 2020). While temperatures are still rising in areas south and south-west of the UK, the increases are statistically non-significant due to the influence of the cold-water anomaly in the North Atlantic (Josey *et al.*, 2018; Tinker and Howes, 2020). Projections are also predicting regional increases and decreases in salinity, reduced oxygen availability and ocean acidification (Dye *et al.*, 2020; Wakelin *et al.*, 2020; Humphreys *et al.*, 2020). For marine mammals, these changes result in geographic range shifts (Kaschner *et al.*, 2011; Ramp *et al.*, 2015; Nøttestad *et al.*, 2015; Williamson *et al.*, 2021); reduction in suitable habitats (particularly sea-ice coverage; Stirling and Derocher, 2012; Laidre *et al.*, 2015); food web alterations (Ramp *et al.*, 2015; Nøttestad *et al.*, 2015; Vikingsson *et al.*, 2015); and increased prevalence of disease in marine mammal populations (Fire and Van Dolah, 2012; Häussermann *et al.*, 2017).

## **WHAT IS ALREADY HAPPENING?**

### ***Range shifts***

The evidence suggests shifts in marine species range are occurring four times faster than for their terrestrial counterparts; on average marine taxa are thought to be moving at a rate of 72 km/decade compared to an average of 17 km/decade in terrestrial taxa (Chen *et al.*, 2011; Poloczanska *et al.*, 2013; Sorte *et al.*, 2010). Pinsky *et al.* (2019) suggest that the differences in rates of change is linked to the smaller thermal tolerances of marine species, resulting in them living much closer to the edges of thermal ranges. By contrast, Pinsky *et al.* (2019) hypothesise that it is more difficult for marine species to avoid warming as water has a much higher heat-transfer rate, and although poorly understood, marine species show limited strategies for heat avoidance, leading them to be impacted by temperature changes more quickly than terrestrial species.

A key observed impact of climate change for marine mammals is range shifts, with increasing evidence that the northern extent of species is shifting further northwards. A study analysing trends in strandings data found that in north-west UK waters (OSPAR Region III North; Figure 1), the proportion of recorded strandings of warm water adapted species (such as short-beaked common dolphin and striped dolphin) has increased over time, while that of cold water adapted species such as Atlantic white-sided and white-beaked dolphins has decreased in these same northern regions indicating changes in

distributions (Figure 2; Hammond *et al.*, 2002; 2013; 2021; Williamson *et al.*, 2021; Coombs *et al.*, 2019). Lower annual mean sea surface temperatures (SST) likely resulted in the shallower trend for OSPARII North, however the increase is still significant (Williamson *et al.*, 2021). In OSPAR II South and OSPAR III South (Figure 1) there was no or little change in the proportion of warm water species stranding (Figure 2). This might be explained by the southern regions of the UK already being part of the range of warm water adapted species, and thus the northward shift in ranges is not captured by stranding records (Williamson *et al.*, 2021).

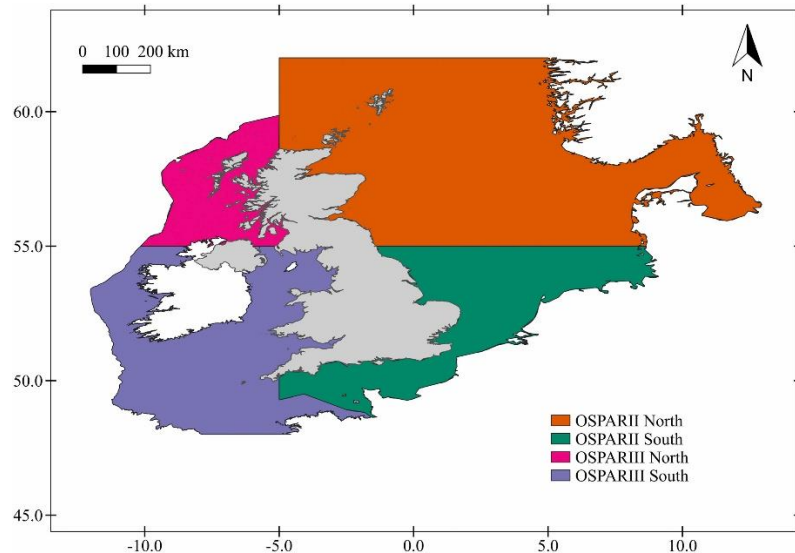


Figure 1: Map of the UK indicating the four regions used for analysis in Williamson *et al.* (2021) OSPAR regions II and III divides UK waters vertically and these were divided further into north and south along the 55° latitude parallel (from Williamson *et al.*, 2021).

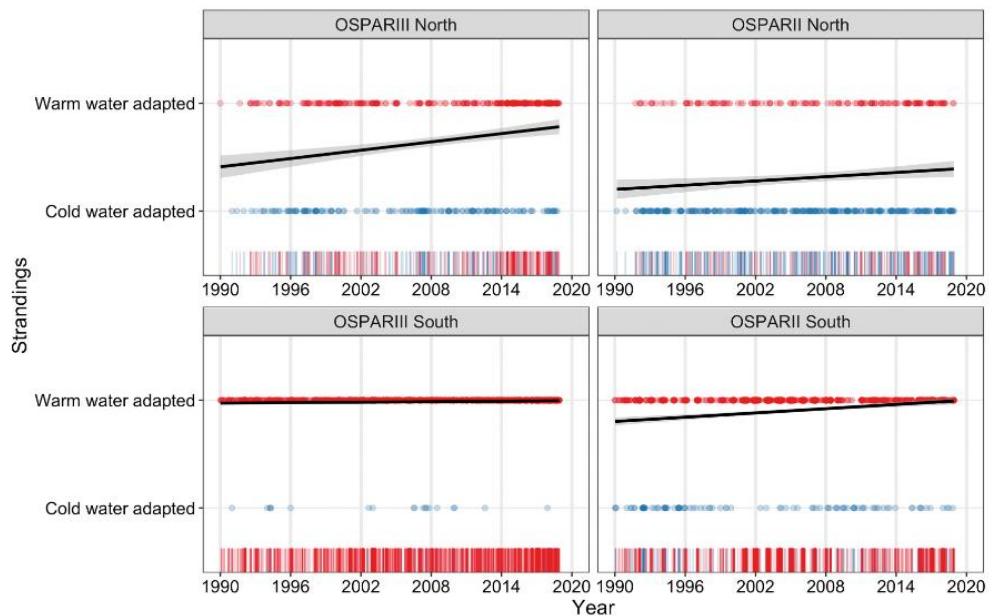


Figure 2: The frequency in strandings of four species of cold water and warm-water cetaceans as a proportion over time, by OSPAR Regions. There are two OSPAR management regions around the UK; OSPAR II (Greater North Sea) and OPSAR III (Celtic Seas). To examine latitudinal differences around the UK these were divided further into north and south zones along the 55° latitude parallel (see map in Figure 1). The frequency of strandings is included as a rug plot along the x-axis and trend lines (black) with 95% error show the change in the proportion of strandings of cold-water species to warm-water species. (From Williamson *et al.*, 2021).

### ***Predator and prey interactions***

Climate-change-driven range shifts of marine mammals might pose new challenges and threats. White-beaked dolphins, found regularly around the Hebrides and Lyme Bay, and seasonally along the north-east coast of England, are more-specialist foragers which restricts their capacity to adapt to change, leaving the species vulnerable to competition by more generalist foraging species such as short-beaked common dolphin (Weir *et al.*, 2009; Jansen *et al.*, 2010; Williamson *et al.*, 2021). In the US Pacific Arctic continued sea ice loss has allowed killer whales to move further north and reach bowhead whales' habitat, increasing the likelihood of predation of killer whales on bowhead whales (Matthews *et al.*, 2020; Willoughby *et al.*, 2020).

These observed shifts in marine mammal distribution are considered to represent a functional response to distribution shifts in their ectothermic (cold-blooded) prey which are more sensitive to environmental changes in UK waters such as increased sea surface temperatures (SSTs) and decreased salinity (Vikingsson *et al.*, 2015; Nottestad *et al.*, 2015; Dye *et al.*, 2020). For example, increased numbers of fin whales and subsequent range expansions into deeper waters in the Irminger Sea, between east Greenland and Iceland, was linked to increased euphausiid abundance in these areas (a key prey species for these animals; Vikingsson *et al.*, 2015). Similarly, harbour porpoise distribution shifts in the North Sea in the last 20 years have been linked to changing sandeel distributions (Hammond *et al.*, 2008; Paxton *et al.*, 2016).

The key timings in the sandeel lifecycle (an important prey species for harbour porpoise) uses the seasonal cycle of copepod production which rely on phytoplankton blooms. With the timing of peaks in copepod abundance shifting, sandeel lifecycles no longer correlate as effectively and recruitment has subsequently declined (van Deurs *et al.*, 2009). However, there is the potential for other species stocks, such as North Sea sprat, another prey source for harbour porpoise, to increase because of increasing temperatures (Pinnegar and Heath, 2010). This shift in the proportion of sprat and sandeel is considered to be a driver of the observed shifts in North Sea harbour porpoise distribution in the early 2000s despite abundance staying relatively stable (Hammond *et al.*, 2008; Hammond *et al.*, 2021; Pinnegar and Heath, 2010).

### ***Role of stratification and the spring bloom***

Climate change impacts the timing, length and strength of summer stratification in the water column, which plays a large role in the occurrence of spring plankton blooms (Holt *et al.*, 2010; Edwards *et al.*, 2020; Wakelin *et al.*, 2020). An overall decline in primary productivity in the north-western European continental shelf by the end of the 21<sup>st</sup> century is predicted due to increased intensity of seasonal stratification limiting the transfer of nutrients throughout the water column (Wakelin *et al.*, 2020). However, there will likely be regional differences; changes in stratification in the eastern Northern North Sea may allow higher retention of nutrients from rivers and increase

primary production (Wakelin *et al.*, 2020). Nevertheless, the predicted changes in length of stratification and subsequent changes in the timing of the bloom may lead to trophic mismatches throughout the food web. These blooms form the basis of the food web, and the timing is important for a wide number of species which co-ordinate key life history events to coincide with these blooms. For example, many fish larvae prey upon the plankton and changes in timing can have significant impacts on successful recruitment. Subsequently, this impacts on prey available to higher marine predators and may result in local changes in distribution as they change foraging strategies or diet, or changes in recruitment success and population dynamics (Wright *et al.*, 2020; Bull *et al.*, 2021; Kebke *et al.*, 2022; Santos and Pierce, 2003).

Copepods have a key linking role in the food web, linking energy transfer from phytoplankton and fish stocks to marine mammal species that prey upon them. Changes in abundance peaks, species composition and distribution also contribute to the wider observed shifts in both prey fish species and marine mammals across seas. Since the 1960s *Calanus finmarchicus* (a typically subarctic copepod species in the northern Atlantic Ocean) has decreased by over 70% (Figure 3; Strand *et al.*, 2020; Evans, 2020). Conversely, warmer-water species such as *Calanus helgolandicus* – usually found in the northern North Sea – is expected to increase (Figure 2; Strand *et al.*, 2020; Evans, 2020). Some of the change is likely due to a northward shift in the species as they follow the 10°C thermal boundary (Beaugrand *et al.*, 2002; Beaugrand *et al.*, 2010). Similarly, Arctic water species, such as *Calanus glacialis* and *Calanus hyperboreus*, are expected to move further northwards as sea temperatures continue to increase (Strand *et al.*, 2020). However, whether the warmer-water species moving northwards will be able to fully replace the Arctic species is yet unclear (Strand *et al.*, 2020; Evans, 2020; Ashlock *et al.*, 2021). Arctic copepod species are larger in biomass, with much higher lipid content than subarctic species (Beaugrand *et al.*, 2010; Søreide *et al.*, 2010). Thus, shifting regional copepod species compositions could reduce the availability of biomass, with a resulting impact across the trophic levels (Søreide *et al.*, 2010; Strand *et al.*, 2020). Further, even if the warmer-water species can fully replace the biomass of the larger Arctic species, each species may have different seasonality which could result in a mismatch between copepods and predators further up the food web (Strand *et al.*, 2020).

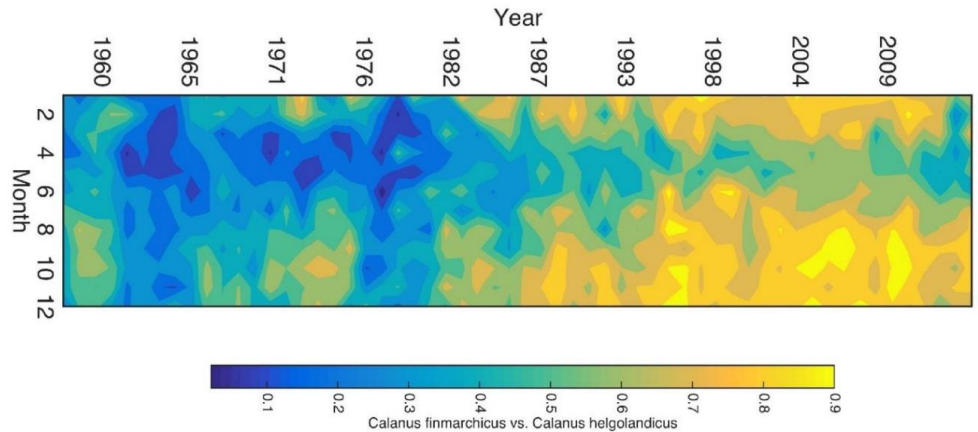


Figure 3: The change in the proportion of the colder-water species *Calanus finmarchicus* (blue/green) to the warmer-water species *Calanus helgolandicus* (yellow) from 1960-2016 in the North Sea. An increase in the proportion of *Calanus helgolandicus* can be seen from the 1980s onwards. (From Edwards et al., 2020).

Increasing SST in the English Channel is linked to declines in body size of multiple copepod species of between 2.93% (*Paracalanus parvus*) and 10.15% (*Temora longicornis*) (Rice et al., 2015; Corona et al., 2021). Further, changes in SST also affect the timing of copepod blooms. Work in the Pacific has demonstrated that the timing of *Neocalanus plumchrus* lifecycles are shifting and warmer spring waters are resulting in earlier peaks in copepod abundance (Ashlock et al., 2021). Similar to changes in phytoplankton blooms described above, the declines in body size and changes in the timing of the copepod blooms may result in trophic mismatches and changes in predator-prey dynamics throughout the food chain (Strand et al., 2020). Ultimately, this may change marine mammal distributions and behaviours if they are required to switch prey or foraging strategies or reproductive success (Bertram et al., 2001; Santos and Pierce, 2003; Bull et al., 2021; Kebke et al., 2022).

### ***Extra-limital records***

Extra-limital records are where a species is recorded outside of its expected range, based on understanding of current distribution. While extra-limital records may be random anomalies (e.g., family outcasts or young animals with less experience of where to find food), unusual environmental conditions can result in extra-limital movements of species. Therefore, sightings or strandings of rare species whose range does not normally lie around the British Isles in recent history, or species recorded around the UK but in unexpected locations might indicate changing conditions, either short-term or long-term. Although these records alone may not be conclusive; when added to the wider picture we can begin to consider whether they are true anomalies or whether they are indicating actual change. Below is a compilation of extra-limital records from strandings data and live sightings from 2013 to 2022 (Table 1). It should be noted that records between 2013 and 2019 are additional to those highlighted in Evans and Waggitt (2020).

Table 1: Extra-limital records of marine mammals around the UK from 2013 to 2022.

Species	Date	Location	Sex	Stranding Type	Date first recorded by CSIP	Comments
<b>Blainville's beaked whale</b>	30/12/2013	Kenneggy Beach, Praa Sands, Cornwall, England	M	Dead	18/07/ 1993	
<b>Pygmy sperm whale</b>	20/11/2014	Newborough, Anglesey, Wales	M	Live	03/10/ 1993	
<b>Pygmy sperm whale</b>	16/05/2015	Wick St Lawrence, Weston-super-Mare, Somerset, England	M	Dead	03/10/ 1993	
<b>Sperm whale</b>	22/01/2016 to 04/02/2016	The Wash, East Anglia, England			09/02/ 1990	Mass stranding of 6 subadult males around the Wash, most likely due to a combination of several environmental factors.
<b>Sperm whale</b>	10/07/2016	Perranporth Beach, Cornwall, England	F	Live	09/02/ 1990	First female to be recorded in the UK.
<b>Pygmy sperm whale</b>	11/06/2019	Ginst Point, Carmarthenshire, Wales	M	Dead	03/10/ 1993	
<b>Sperm whale</b>	29/10/2019	Hell's Mouth, Gwynedd, Wales	M	Live	09/02/ 1990	
<b>Killer whale</b>	06/12/2019	RAF Holbeach, Lincolnshire, England	M	Dead	25/04/ 1995	First recording of a killer whale stranding in the area for 16 years.
<b>Blainville's beaked whale</b>	01/07/2020	Hallelujah Bay, Portland, Dorset, England	M	Dead	18/07/ 1993	
<b>Walrus</b>	03/2021 to 08/2021	West Coast of UK	M			Sighted frequently along the western coast of the UK from March to August 2021
<b>Beluga</b>	20/07/2021	Unst, Shetland				First sighting of a beluga whale off Shetland since 1997.
<b>Walrus</b>	09/2021	Northumberland, England	F			
<b>Pygmy sperm whale</b>	09/12/2021	Hive Beach, Burton Bradstock, Dorset, England	M	Dead	03/10/ 1993	
<b>Atlantic white-sided dolphin</b>	03/07/2022	Greenbank Cove, Portreath, Cornwall, England	M	Dead	11/01/ 1991	

Data on cetaceans (except for beluga whale sighting) comes from CSIP stranding database ([ukstrandings.org/csip-reports/](http://ukstrandings.org/csip-reports/)).

Information on the beluga whale sighting comes from local news reports ([www.shetnews.co.uk/2021/07/21/first-local-sighting-of-beluga-whale-in-nearly-25-years/](http://www.shetnews.co.uk/2021/07/21/first-local-sighting-of-beluga-whale-in-nearly-25-years/))

Data on the walrus sightings comes from anecdotal information, the NBN atlas (<https://nbnatlas.org/>) and news articles ([www.nhm.ac.uk/discover/news/2021/march/rare-walrus-sighting-in-ireland.html](http://www.nhm.ac.uk/discover/news/2021/march/rare-walrus-sighting-in-ireland.html), [www.bbc.co.uk/news/uk-england-tyne-59282114](http://www.bbc.co.uk/news/uk-england-tyne-59282114)).

### ***Summary of marine mammal abundance trends and distribution in UK regional waters***

Given its position between the warmer waters of southern Europe and North Africa, as well as the colder waters of the Arctic, the UK sits at the edge of thermal tolerances for both cold-water and warm-water adapted species and is particularly well located to observe climate-driven changes in marine mammal populations (Williamson *et al.*, 2021; Sonnewald and Lguensat, 2021).

The shorter time interval since the publishing of Evans and Waggitt (2020), coupled with the likely impacts of Covid-19 on the ability to carry out monitoring and assessments, means that the evidence provided in previous MCCIP reviews is still applicable (Evans and Bjørge, 2013; Evans and Waggitt, 2020) and that new evidence of marine mammal trends in UK waters is more limited. Seal monitoring and reporting in the UK has continued on a smaller scale through the Special Committee on Seals and regional surveys (<http://www.smru.st-andrews.ac.uk/scos/>). New information since the 2020 report is presented here, alongside additional information from the last reporting period.

There is increasing evidence of several species undergoing shifts in their distributions around the UK, both annually and seasonally. As already noted (Figure 2), analysis of stranding records show a significant change in the proportion of records for four pilot species in eastern and north-western waters of the UK, indicating the range of these species may be changing with typically warmer water species moving further northwards (Williamson *et al.*, 2021). These changes were linked to changing SSTs; significant increases in SST have been observed in eastern and north-western UK but not south-western UK (Williamson *et al.*, 2021).

Range shifts have been observed in several inshore UK bottlenose dolphin populations over the last decade. Individuals from a population which historically use the Moray Firth Special Area of Conservation (SAC) in the north-east of Scotland are now frequently observed further south towards St Andrews Bay and the Tay estuary, suggesting either a shift in the core range or a southerly expansion (Cheney *et al.*, 2013, 2014; Arso Civil *et al.*, 2019). However, further research is required to better understand how and why the population is changing (Gutierrez-Munoz, 2021). Similarly, in the south-west of England, the semi-resident bottlenose dolphin population previously observed on the southern coasts of Devon and Cornwall may now be extending throughout the English Channel, with sightings recorded from the Bristol Channel and as far east as Sussex (Dudley, 2017; Corr, 2020; Duncan, 2021). On the west coast of Ireland in the Shannon Estuary, there is evidence that the resident population of bottlenose dolphins is expanding beyond the range of the current Lower River Shannon SAC into Brandon Bay, with individuals sighted here on 92% of surveyed days and foraging behaviour



observed over 20% of the survey period (Charish *et al.*, 2021). However, there is some evidence which indicates the population is beginning to decline and adult mortality increasing from 3.8% to 7% (Blázquez *et al.*, 2020). In Wales, surveys suggest the proportion of known individuals within the Cardigan Bay SAC has decreased, and that the residents might have larger home ranges than previously thought (Lohrengel *et al.*, 2017). Further monitoring and photo-identification surveys would be needed around Wales to fully understand the distribution of bottlenose dolphins around Wales (Lohrengel *et al.*, 2017).

Large-scale trends in grey and harbour seal abundance that were reported on in Evans and Waggitt (2020) are still relevant, however, more recent regional shifts are apparent. Overall, UK grey seal pup production has increased by <1.5% per year between 2016 and 2019 (SCOS, 2021). Growth has been concentrated largely along the eastern coast of Scotland and England, increasing by 23% between 2016 and 2019, while pup production is estimated to have reduced by 3.3% in the same period on the west coast of Scotland (SCOS, 2021). In Wales, there is evidence that in monitored grey seal colonies on Ramsey Island, pup production is increasing; 380 pups were born between August 2015 and December 2016, higher than both the 1992–1996 mean of 217 pups and the 2011–2015 mean of 343 pups (Morgan *et al.*, 2018).

Overall, the UK population of harbour seals has continued to increase and is now reported to be close to those levels recorded prior to the 2002 phocine distemper virus outbreak. Counts have increased from 25,600 between 2007–2009 to 31,500 between 2016 and 2021. Regionally, however, significant variations in population abundance are ongoing. Observed declines have continued along the east coast of Scotland and Northern Isles, while populations along the west coast of Scotland are either stable or increasing. Harbour seal abundance had increased annually along the south-east of England coast until 2019 when the count was identified to be 27.6% lower than the 2012–2018 mean. Since this time surveys in both 2020 and 2021 have confirmed the decline (SCOS, 2021).

Grey seal and harbour seal numbers around Ireland appear to be increasing, although surveys are much less regular than in other regions. Harbour seal counts around the Republic of Ireland in August 2017–18 estimated 4007 animals, substantially higher than counts from 2011/12 when numbers were estimated at 2955 (ICES, 2021). In the Republic of Ireland estimates of grey seal abundance of between 7284 – 9356 from surveys throughout 2009–2012 were significantly higher than in the mid-1990s (Ó Cadhla *et al.*, 2013). Surveys in 2017–2018 confirmed this increase (Morris and Duck, 2019). No evidence has been given to explain the changes. There is uncertainty when predicting the effects of climate change on seals, however indirect effects of climate change such as changes in prey distribution and/or availability, increases in harmful algal blooms (HABs) and increases in disease prevalence are considered to possibly impact UK harbour seal populations in the future (SCOS, 2021). It should be noted that seal counts only include animals which were on land during surveys and so, counts only indicate population trends rather than absolute population numbers.

## WHAT COULD HAPPEN IN THE FUTURE?

As with previous MCCIP reviews, there continues to be limited understanding about how marine mammals are responding to climate change. This is due to the difficulties associated with monitoring marine mammals (e.g., deep diving and highly mobile species) which makes identification of short-term trends difficult, and the multiple pressures (including offshore developments of human infrastructures, commercial fisheries, chemical pollution) they face which make it difficult to distinguish the specific impacts of climate change (Ballance, 2018; Boyd *et al.*, 2010). Furthermore, present climate change is occurring much more rapidly than any previous changes and available evidence of historical adaptations of marine mammals may not reflect present adaptations to climate change (Intergovernmental Panel on Climate Change, 2021; Cabrera *et al.*, 2022). As a result, predicting future impacts remains difficult. Evidence maintains support for the theory that range shifts will continue as animals follow ectothermic prey or attempt to remain within thermal preferences (see Williamson *et al.*, 2021 and Coombs *et al.*, 2019 for two examples since the last MCCIP review). This could result in species diversity increasing in mid-latitudes (Whitehead *et al.*, 2008; Kaschner *et al.*, 2011; Evans and Waggitt, 2020). However, the issue is complex and, for example, while an assessment might predict an increase in range, habitat loss elsewhere may ultimately result in overall declines for some populations in the future (SCOS, 2018; Evans and Waggitt, 2020). Furthermore, some species might be more flexible to the changing conditions than others; species which are more generalist in either habitat type or prey type might be better able to adapt to the changes than species which have specific requirements in habitat, prey or environmental condition (Weir *et al.*, 2009; Jansen *et al.*, 2010; Burek *et al.*, 2008).

### *Range shifts*

Colder-water species should be expected to experience large impacts from climate change and associated ocean warming due to the more-limited area in which to expand ranges to adapt and the more-rapid rates of change happening in polar regions (Simmonds and Isaac, 2007; Moore and Reeves, 2018; Laidre *et al.*, 2008). Conversely, the decline in sea ice and the release of primary productivity this brings may allow some species such as the bowhead whale to thrive and adapt (Moore, 2016; Moore and Reeves, 2018). Cabrera *et al.* (2022) noted that after the Last Glacial Maximum, baleen whales increased in abundance due to changes in the prey availability while the longer ice-free period allows them to arrive earlier in feeding grounds and have more time in which to build stores for the next breeding season (Ramp *et al.*, 2015).

However, while the reduction in sea ice might allow baleen whales more time in foraging grounds, rising SSTs are putting several key humpback whale breeding grounds at risk of exceeding the current upper thermal limit (21–28°C), which will likely result in a range change if this trend continues (Sydeman *et al.*, 2015; Derville *et al.*, 2019). Range shifts would require suitable habitats elsewhere, which still allow for the required behaviours such

as social aggregation or effective transmission of male song as part of attracting a mate (Derville *et al.*, 2019). Therefore, instead of range shifts, humpback whales may respond to rising SSTs by shifting the timings of migrations between feeding and breeding grounds (although timing could be more closely tied to environmental conditions in feeding grounds; Ramp *et al.*, 2015) or they might move into deeper, offshore waters where temperatures are cooler (von Hammerstein *et al.*, 2022). For UK waters, the increasing SST could lead to earlier use of the migration corridor along the west coast influencing the ecosystem services they provide (Johnson *et al.*, 2022).

While much of the current evidence suggests that the key changes in marine mammals will correlate with changing prey locations as they track temperature niches in the environment, not all will follow this general pattern. As endotherms, marine mammals can thermoregulate and consequently, they should theoretically be able to adapt to the direct impacts of changes in SST (Evans, 2020). However, as temperatures move further away from the optimum range, they will need more energy to regulate their temperature and it may become less energetically costly for them to track the changing temperatures (Sanderson and Alexander, 2020). For example, the distribution of pilot whale populations in the north-west Atlantic has shifted northward at a faster rate than expected and more than three times the rate of their preferred prey species are (Thorne and Nye, 2021). Here it was concluded that pilot whales are reacting to directly to changes in SST (Thorne and Nye, 2021). Premature range shifts are also hypothesised to allow for a competitive advantage; ectothermic prey species may show slower swimming speeds and impaired visual activities in cooler waters (Thorne and Nye, 2021; Grady *et al.*, 2019). As a result, in cooler waters it may be easier for the predators to capture prey and ultimately, increase the net energy gained from each prey item (Grady *et al.*, 2019).

### ***Ecosystem services***

Cetaceans play a key role in normal ecosystem functioning through influences on the global carbon budget, nutrient cycling, risk effects, assisting foraging in other species and climate regulation (Grebmeier and Harrison, 1992; Kiszka *et al.*, 2015; Sheehy *et al.*, 2022). For example, large whales help redistribute sediment and nutrients throughout the water column, promoting phytoplankton growth and bringing prey sources to the surface for other species (Alter *et al.*, 2015; Chami *et al.*, 2020). Their large-scale movements throughout the ocean also help with the lateral movement of nutrients, connecting otherwise separate food webs (Roman *et al.*, 2014). They also provide a key role in climate regulation through carbon sequestration, with cetacean populations around the UK estimated to contain 2 million tonnes of Carbon and contribute up to 22 million tonnes of Carbon per year to carbon fluxes (Sheehy *et al.*, 2022). Thus, changes in marine mammal behaviours and range shifts can have large impacts on ecosystem dynamics and the services that the marine environment can provide (Sheehy *et al.*, 2022; Watson *et al.*, 2020; Chami *et al.*, 2019). Changes in their use of the marine environment and their distributions could result in large-scale declines in

overall biodiversity and ecosystem health. Alternatively, protection of them could help reduce CO<sub>2</sub> in the atmosphere and help towards mitigation of future climate change (Chami *et al.*, 2019).

### ***Infectious disease***

As with the previous review (Evans and Waggitt, 2020), the main mechanisms by which increasing SSTs impact on disease prevalence are still thought to be through range shifts for both hosts and pathogens introducing novel pathogens to new species and areas, increase in favourable conditions for the pathogen allowing higher survival rates, and increased thermal stress of the marine mammals increasing susceptibility to disease (Cohen *et al.*, 2018; Tracy *et al.*, 2019; Sanderson and Alexander, 2020). Recent analysis of infectious disease mass-mortality events throughout the last century saw a correlation with rising sea surface temperatures and infectious diseases on a global and regional scale (Sanderson and Alexander, 2020). Pinnipeds that use both terrestrial and marine environments are likely to be more impacted than cetaceans due to their increased exposure to pathogens that occur in both types of environments (Patz *et al.*, 2004; Sanderson and Alexander, 2020).

However, while evidence is growing that infectious diseases will increase, studies have suggested that increases in temperature will only favour them to a point (Studer *et al.*, 2010). If poleward range-shifts are increasing biodiversity at mid-latitudes (Whitehead *et al.*, 2008; Kaschner *et al.*, 2011; Evans and Waggitt, 2020), then it could be expected that disease will decrease in this region because of climate change. Increased biodiversity can reduce the spread of disease through the dilution effect whereby the occurrence of many hosts, some better than others, can decrease the likelihood of infection of 'good' hosts who will pass the disease on (Civitello *et al.*, 2015). Studies looking at disease prevalence as a result of climate change often do not consider the impacts of transmission dynamics which can act in contrast to measured parameters. For example, while climate change might increase the prevalence of pathogens and susceptibility of hosts, changing environmental conditions may also decrease survival rate of hosts, therefore decreasing the transmission of disease within a population (Lafferty and Holt, 2003). More work is needed incorporating these aspects of disease transmission to determine the impacts of climate change on marine diseases, and the impact on marine mammals.

In addition, the literature continues to suggest that harmful algal blooms (HABs) around the United Kingdom are increasing (including Van Dolah, 2000; Peperzak, 2003; Broadwater *et al.*, 2018). Brown *et al.* (2022) have described that HABs in the western English Channel are increasing in both extent and duration due to increased SST. These release biotoxins which can accumulate up the food chain from filter-feeding shellfish to higher marine predators such as marine mammals (Ben-Gigirey *et al.*, 2021; Scholin *et al.*, 2000). With increased HABs, poisonings in marine mammals are also at risk of increasing potentially leading to impaired physiological functions, poorer body condition and increased disease (Geraci and Lounsbury, 2002; SCOS, 2018; Burek *et al.*, 2008; Broadwater *et al.*, 2018). Increased frequency of

HABs has also been linked to reduction in prey species and plankton, resulting in reduced prey availability for marine mammals (Smit *et al.*, 2021; Siano *et al.*, 2020; Bresnan *et al.*, 2021).

### ***Reproduction***

Breeding dynamics and demography of pinniped species may also change with continued climate change (Smout *et al.* 2019; Bull *et al.*, 2021; Caillat *et al.*, 2019). When faced with insufficient resources, animals are required to ‘trade off’ between survival and reproduction (Stearns, 1992). For species with multiple reproduction opportunities over their lifetime, trade-offs may occur between current and future reproduction. Individual traits and age may influence opportunity to build up the required resources however, environmental conditions may also play a large role with individuals more likely to forgo breeding in suboptimal conditions (Beauplet *et al.*, 2006; Forcada *et al.*, 2008). However, in older individuals, with less future reproductive opportunities, the energetic trade offs they face could prioritise current breeding (Goutte *et al.*, 2010). This might explain the current observation that mean pupping date is occurring earlier in UK grey seals. Current changes in environmental conditions (temperature, prey abundance and distribution, etc.) could result in suboptimal conditions, and where younger individuals are skipping breeding attempts, older females (who are known to pup earlier in the season) are prioritising reproduction (Bull *et al.*, 2021; Smout *et al.*, 2019; Goutte *et al.*, 2010). It may also be that the more experienced, older females have more stored resources that they can rely on (LeBoeuf *et al.*, 2019).

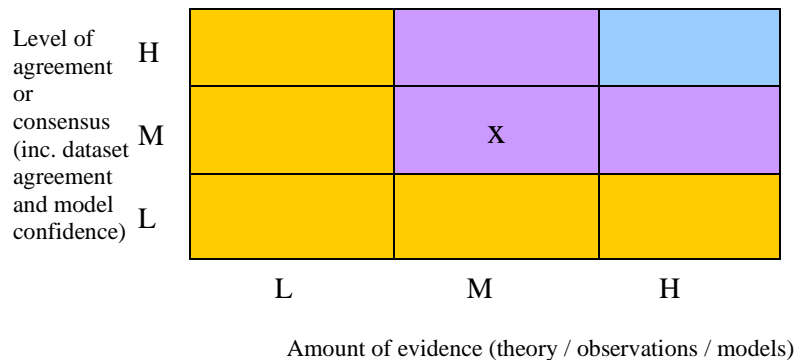
If environmental change does result in an increase in older mothers who pup earlier in the season (both of which are seen to increase the likelihood of the pup being successfully raised to weaning), environmental change has the potential to improve population growth and resilience of the population. However, changing conditions may result in females skipping multiple reproductive seasons and this may have negative impacts on population structure (Bull *et al.*, 2021; Smout *et al.*, 2019). Conclusions are limited by issues in assessing breeding status and missed opportunities – when you do not see them, they might not be breeding or they may simply not have been observed (Smout *et al.*, 2019). Further, with range shifts happening around the UK, it could be that they have moved haul-out sites (Bull *et al.*, 2021). It may also be site specific – grey seal pup survival was shown to be highly varied between sites and there was little correlation between nearby sites (Engbo *et al.*, 2020). Ultimately, while evidence suggests some impact of climate change the reproductive success of pinnipeds, more work is needed to better understand the potential impacts, and the role site selection will play.

Similar principles may also apply for reproduction in cetaceans. Marine heatwaves and the resulting mass mortalities of species at lower trophic levels, and changes in ecosystem structures have been linked to significant declines in reproduction rates in Indo-Pacific bottlenose dolphins in Shark Bay (Western Australia) and humpback whales in both Hawaii and Canada (Wild *et al.*, 2019; Cartwright *et al.*, 2019; Kershaw *et al.*, 2021). Females

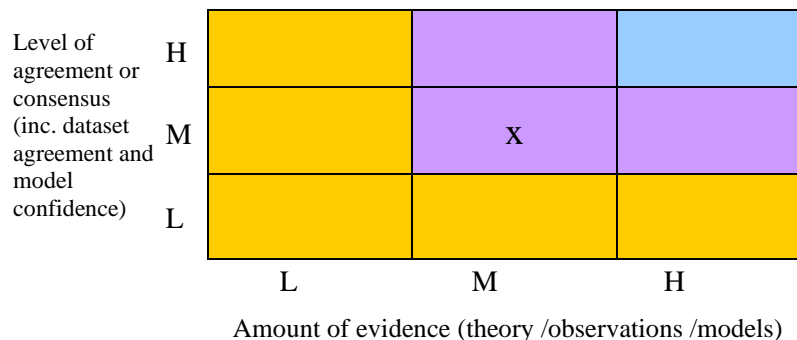
faced with low prey availability and in poorer body condition (typically measured by blubber thickness) may have a higher likelihood of early-term abortions or less investment in the foetus as they prioritise their own survival over the reproductive attempt (Miller *et al.*, 2011; Christiansen *et al.*, 2014; Knowlton *et al.*, 1994). They may also have suppressed ovulation or reach sexual maturity later (Boyd *et al.*, 1999), indicating the potential for long-term impacts of climate change of reproduction in cetacean populations, through changes in prey availability. However, using blubber thickness as a sole metric of body condition is not always a reliable estimate of the energy available for reproduction (Derosus *et al.*, 2020; Evans *et al.*, 2003; Gómez-Campos *et al.*, 2011). For many species, blubber has other uses beyond energy storage, and the structure and content of the blubber may change before thickness does, making them a more reliable indication of the energy storage available to an individual (Ball *et al.*, 2015). Further, the impacts of climate change beyond prey availability such as ocean acidification and atmospheric CO<sub>2</sub> levels and how they respond to cumulative pressures is less well studied (Kebke *et al.*, 2022). Thus, the impacts of climate change on reproduction in cetaceans remain uncertain and more work is needed to look at the physiological responses of cetaceans to poor environmental conditions (Kebke *et al.*, 2022).

### CONFIDENCE ASSESSMENT

#### *What is already happening?*



#### *What could happen in the future?*



The evidence for range shifts in several cetacean species in waters around the United Kingdom has increased since the last report. In addition, there have

been more reports noting increasing occurrence of disease or novel diseases and fatal poisonings from HABs (Sanderson and Alexander, 2020; Tracy *et al.*, 2019; Byers, 2021). However, more work is needed to understand the impacts of environmental variables beyond temperature (including ocean acidity, dissolved oxygen concentration, and salinity), to better understand the variability in responses of both hosts and pathogens, and to distinguish the impacts of climate change from other pressures in the environment or determine the causal relationships (many of the effects of climate change are indirect and determining causation from correlation can be difficult; Berkhout *et al.*, 2014; Byers, 2021). Beyond this, there has been little published that might help improve our confidence assessments overall.

## **KEY CHALLENGES AND EMERGING ISSUES**

Many of the key challenges highlighted in previous MCCIP reviews (Evans and Bjørge, 2013; Evans and Waggitt, 2020) are still applicable. The primary challenge is **long-term monitoring** of marine mammals around the UK to enable identification of changes in distribution and abundance over time as well as trends in infectious diseases, strandings and changes in phenology. There have been some advances which may lead to improved understanding of the impacts of climate change on marine mammals but uneven coverage throughout the UK, infrequent large-scale surveys, and patchy regional surveys still hinders assessment of trends. There is commitment in principle across many NE Atlantic countries to increase frequency of large-scale survey which would support robust analysis of population trends. Programmes which aim to mobilise and standardise data for marine mammals are being developed such as the Joint Cetacean Data Programme which collates effort-related cetacean data in a standardised format, making it available for analyses to improve capacity to identify trends at different spatial and temporal scales ([jncc.gov.uk/our-work/joint-cetacean-data-programme/](http://jncc.gov.uk/our-work/joint-cetacean-data-programme/)). More-frequent large-scale data collection and the collation of other sources of monitoring data into an accessible resource may also help define current baselines from which favourable reference values can be developed and allow better assessment of the conservation status of species (Bijlsma *et al.*, 2018).

There is an increasing number of marine renewable energy developments to combat climate change. The impacts of these combined with natural physical changes will create **cumulative effects** which need to be accounted for to properly understand how marine mammals will react to climate change. To address this increase, long-term data gathering is needed alongside the development and application of analysis techniques such as agent-based models (ABMs) and Ecopath with Ecosim (EwE) (Chudzinska *et al.*, 2021; McClintock *et al.*, 2013; Christensen and Walters, 2004). Both have their limitations – ABMs need very detailed spatial information for the species, and EwE models are associated with many uncertainties – but with development both could be useful tools for assessing the long-term cumulative impacts in marine systems (Serpetti *et al.*, 2017; Trifonova *et al.*, 2022).

Another key challenge is getting a better understanding of animals' behaviours and physiology and how they respond to **bottom-up changes** from lower trophic levels. Evidence for the ability of many marine mammals to switch foraging and diet strategies based on availability in their environment will likely vary between species. Some prey species are more energetically beneficial than others (Santos and Pierce, 2003). Thus, switches may incur costs which present in fecundity or survival rates or may lead to further distribution shifts. Development of analytical models, like those described above, to include prey energy densities and predator energy requirements will help improve the understanding of how marine mammals might need to adjust foraging behaviours to still meet energy needs.



## REFERENCES

- Alter, S.E., Meyer, M., Post, K., Czechowski, P., Gravlund, P., Gaines, C., Rosenbaum, H.C., Kaschner, K., Turvey, S.T., van der Plicht, J. and Shapiro, B. (2015) Climate impacts on transoceanic dispersal and habitat in gray whales from the Pleistocene to 2100. *Molecular Ecology*, **24**(7), 1510-1522.
- Arso Civil, M., Quick, N.J., Cheney, B., Pirotta, E., Thompson, P.M. and Hammond, P.S. (2019) Changing distribution of the east coast of Scotland bottlenose dolphin population and the challenges of area-based management. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **29**, 178-196.
- Ashlock, L., García-Reyes, M., Gentemann, C., Batten, S. and Sydeman, W. (2021) Temperature and patterns of occurrence and abundance of key copepod taxa in the Northeast Pacific. *Frontiers in Marine Science*, **8**, 670795.
- Ball, H.C., Stavarz, M., Oldaker, J., Usip, S., Londraville, R.L., George, J.C., Thewissen, J.G. and Duff, R.J. (2015) Seasonal and ontogenetic variation in subcutaneous adipose of the bowhead whale (*Balaena mysticetus*). *The Anatomical Record*, **298**(8), 1416-1423.
- Ballance, L.T. (2018) Cetacean ecology. In *Encyclopedia of Marine Mammals*. Academic Press, pp. 172-180.
- Beaugrand, G., Reid, P.C. and Ibañez, F. (2002) Reorganization of North Atlantic marine copepod biodiversity and climate. *Science*, **296**, 1692-1694.
- Beaugrand, G., Edwards, M. and Legendre, L. (2010) Marine biodiversity, ecosystem functioning, and carbon cycles. *Proceedings of the National Academy of Sciences*, **107**, 10120-10124.
- Beauplet, G., Barbraud, C., Dabin, W., Küssener, C. and Guinet, C. (2006) Age-specific survival and reproductive performances in fur seals: Evidence of senescence and individual quality. *Oikos*, **112**(2), 430-441.
- Ben-Gigirey, B., Soliño, L., Bravo, I., Rodríguez, F. and Casero, M.V. (2021) Paralytic and amnesic shellfish toxins impacts on seabirds, analyses and management. *Toxins*, (7), 454.
- Berkhout, B.W., Lloyd, M.M., Poulin, R. and Studer, A. (2014) Variation among genotypes in responses to increasing temperature in a marine parasite: evolutionary potential in the face of global warming?. *International Journal for Parasitology*, **44**(13), 1019-1027.
- Bertram, D.F., Mackas, D.L. and McKinnell, S.M. (2001) The seasonal cycle revisited: interannual variation and ecosystem consequences. *Progress in Oceanography*, **49**(1-4), 283-307.
- Bijlsma, R.J., Agrillo, E., Attorre, F., Boitani, L., Brunner, A., Evans, P. et al. (2018) Defining and applying the concept of Favourable Reference Values for species and habitats under the EU birds and Habitats Directives. Technical Report for the EC service contract no 07.0202/2015/715107/SER/ENV.B.3.
- Blázquez, M., Baker, I., O'Brien, J.M. and Berrow, S.D. (2020). Population viability analysis and comparison of two monitoring strategies for bottlenose dolphins (*Tursiops truncatus*) in the Shannon Estuary, Ireland, to Inform Management. *Aquatic Mammals*, **46**(3), 307-325.
- Boyd, I.L., Lockyer, C.H. and Marsh, H.D. (1999) Reproduction in marine mammals. In *Biology of Marine Mammals*, Washington, D.C.: Smithsonian Institution Press, pp. 218-286.
- Boyd, I.L., Bowen, W.D. and Iverson, S.J. eds. (2010) *Marine Mammal Ecology and Conservation: a Handbook of Techniques*. Oxford University Press, 431 pp.
- Bresnan, E., Arévalo, F., Belin, C., Branco, M.A., Cembella, A.D., Clarke, D., Correa, J., Davidson, K., Dhanji-Rapkova, M., Lozano, R.F. and Fernández-Tejedor, M. (2021) Diversity and regional distribution of harmful algal events along the Atlantic margin of Europe. *Harmful Algae*, **102**, 101976.
- Broadwater, M.H., Van Dolah, F.M. and Fire, S.E. (2018) Chapter 5. Vulnerabilities of Marine Mammals to Harmful Algal Blooms. In *Harmful Algal Blooms: A Compendium Desk Reference* (eds Shumway, S.S., Burkholder, J.M. and Morton, S.L.), Wiley Publishers, 696 pp.
- Brown, A.R., Lilley, M.K., Shutler, J., Widdicombe, C., Rooks, P., McEvoy, A., Torres, R., Artioli, Y., Rawle, G., Homyard, J. and Tyler, C.R. (2022) Harmful Algal Blooms and their impacts on shellfish mariculture follow regionally distinct patterns of water circulation in the western English Channel during the 2018 heatwave. *Harmful Algae*, **111**, 102166.
- Bull, J.C., Jones, O.R., Börger, L., Franconi, N., Banga, R., Lock, K. and Stringell, T.B. (2021) Climate causes shifts in grey seal phenology by modifying age structure. *Proceedings of the Royal Society B*, **288**(1964), 20212284.
- Burek, K.A., Gulland, F.M.D. and O'Hara, T.M. (2008) Effects of climate change on Arctic marine mammal health. *Ecological Applications*, **18**, S126-S134.
- Byers, J.E. (2021). Marine parasites and disease in the era of global climate change. *Annual Review of Marine Science*, **13**, 397-420.
- Cabrera, A.A., Schall, E., Bérubé, M., Anderwald, P., Bachmann, L., Berrow, S., Best, P.B., Clapham, P.J., Cunha, H.A., Dalla Rosa, L. and Dias, C. (2022) Strong and lasting impacts of past global warming on baleen whales and their prey. *Global Change Biology*, **28**(8), 2657-2677.

- Caillat, M., Cordes, L., Thompson, P., Matthiopoulos, J. and Smout, S. (2019) Use of state-space modelling to identify ecological covariates associated with trends in pinniped demography. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **29**, 101-118.
- Cartwright, R., Venema, A., Hernandez, V., Wyels, C., Cesere, J. and Cesere, D. (2019) Fluctuating reproductive rates in Hawaii's humpback whales, *Megaptera novaeangliae*, reflect recent climate anomalies in the North Pacific. *Royal Society Open Science*, **6**(3), 181463.
- Chami, R., Cosimano, T.F., Fullenkamp, C. and Oztosun, S. (2019) Nature's Solution to Climate Change: A strategy to protect whales can limit greenhouse gases and global warming. *Finance and Development*, **56**(004).
- Chami, R., Fullenkamp, C., Berzaghi, F., Español-Jiménez, S., Marcondes, M. and Palazzo, J. (2020) On valuing nature-based solutions to climate change: a framework with application to elephants and whales. ERID Working Paper 297.
- Charish, R., Berrow, S. and O'Brien, J. (2021) Acoustic monitoring of a bottlenose dolphin (*Tursiops truncatus*) population: trends in presence and foraging beyond the limits of the Lower River Shannon SAC. *Journal of Marine Science and Engineering*, **9**(6), 650.
- Chen, I.C., Hill, J.K., Ohlemüller, R., Roy, D.B. and Thomas, C.D. (2011) Rapid range shifts of species associated with high levels of climate warming. *Science*, **333**(6045), 1024-1026.
- Cheney, B., Thompson, P.M., Ingram, S.N., Hammond, P.S., Stevick, P.T., Durban, J.W., Culloch, R.M., Elwen, S.H., Mandleberg, L., Janik, V.M. and Quick, N.J. (2013) Integrating multiple data sources to assess the distribution and abundance of bottlenose dolphins *Tursiops truncatus* in Scottish waters. *Mammal Review*, **43**(1), 71-88.
- Cheney, B., Corkrey, R., Durban, J.W., Grellier, K., Hammond, P.S., Uslas-Villanueva, V., Janik, V.M., Lusseau, S.M., Parsons, K.M., Quick, N.J., Wilson, B. and Thompson, P.M. (2014) Long-term trends in the use of a protected area by small cetaceans in relation to changes in population status. *Global Ecology and Conservation*, **2**, 118-128.
- Christensen, V. and Walters, C.J. (2004) Ecopath with Ecosim: methods, capabilities and limitations. *Ecological Modelling*, **172**(2-4), 109-139.
- Christiansen, F., Víkingsson, G.A., Rasmussen, M.H. and Lusseau, D. (2014) Female body condition affects foetal growth in a capital breeding mysticete. *Functional Ecology*, **28**(3), 579-588.
- Chudzinska, M., Nabe-Nielsen, J., Smout, S., Aarts, G., Brasseur, S., Graham, I., Thompson, P. and McConnell, B. (2021) AgentSeal: Agent-based model describing movement of marine central-place foragers. *Ecological Modelling*, **440**, 109397.
- Civitello, D.J., Cohen, J., Fatima, H., Halstead, N.T., Liriano, J., McMahon, T.A., Ortega, C.N., Sauer, E.L., Sehgal, T., Young, S. and Rohr, J.R. (2015) Biodiversity inhibits parasites: broad evidence for the dilution effect. *Proceedings of the National Academy of Sciences*, **112**(28), 8667-8671.
- Cohen, R.E., C.C. James, C.C., Lee, A., Martinelli, M.M., Muraoka, W.T. *et al.* (2018) Marine host-pathogen dynamics: Influences of global climate change. *Oceanography*, **31**(2), 182-193.
- Coombs, E.J., Deaville, R., Sabin, R.C., Allan, L., O'Connell, M., Berrow, S., Smith, B., Brownlow, A., Doeschate, M.T., Penrose, R. and Williams, R. (2019) What can cetacean stranding records tell us? A study of UK and Irish cetacean diversity over the past 100 years. *Marine Mammal Science*, **35**(4), 1527-1555.
- Corona, S., Hirst, A., Atkinson, D. and Atkinson, A. (2021) Density-dependent modulation of copepod body size and temperature-size responses in a shelf sea. *Limnology and Oceanography*, **66**(11), 3916-3927.
- Corr, S. (2020). Using citizen science data to assess the vulnerability of bottlenose dolphins (*Tursiops truncatus*) along England's south coast. MSc Thesis, University of Plymouth.
- Derous, D., ten Doeschate, M., Brownlow, A.C., Davison, N.J. and Lusseau, D. (2020) Toward new ecologically relevant markers of health for cetaceans. *Frontiers in Marine Science*, 367. [doi.org/10.3389/fmars.2020.00367](https://doi.org/10.3389/fmars.2020.00367)
- Derville, S., Torres, L.G., Albertson, R., Andrews, O., Baker, C.S., Carzon, P., Constantine, R., Donoghue, M., Dutheil, C., Gannier, A. and Oremus, M. (2019) Whales in warming water: Assessing breeding habitat diversity and adaptability in Oceania's changing climate. *Global Change Biology*, **25**(4), 1466-1481.
- Dudley, R.H. (2017) Using citizen science data to assess the social structure, residency and distribution of bottlenose dolphins (*Tursiops truncatus*) in southwest England. MSc Thesis, University of Plymouth.
- Dulvy, N.K., Rogers, S.I., Jennings, S., Stelzenmüller, V., Dye, S.R. and Skjoldal, H.R. (2008) Climate change and deepening of the North Sea fish assemblage: a biotic indicator of warming seas. *Journal of Applied Ecology*, **45**(4), 1029-1039.
- Duncan, S. (2021) Is conservation management fit for purpose: a case study using a small coastal resident bottlenose dolphin (*Tursiops truncatus*) population. MSc Thesis, University of Plymouth.
- Dye, S., Berx, B., Opher, J., Tinker, J.P. and Renshaw, R. (2020) Climate change and salinity of the coastal and marine environment around the UK. *MCCIP Science Review*, 2020, 76-102.
- Edwards, M., Atkinson, A., Bresnan, E., Helaoet, P., McQuatters-Gollup, A., Ostle, C., Pitois, S. and Widdicombe, C. (2020). Plankton, jellyfish and climate in the North-East Atlantic. *MCCIP Science Review*, 2020, 322-353.

- Engbo, S., Bull, J.C., Börger, L., Stringell, T.B., Lock, K., Morgan, L. and Jones, O.R. (2020). Census data aggregation decisions can affect population-level inference in heterogeneous populations. *Ecology and evolution*, 10(14), 7487-7496.
- Evans, K., Hindell, M.A. and Thiele, D. (2003) Body fat and condition in sperm whales, *Physeter macrocephalus*, from southern Australian waters. *Comparative Biochemistry and Physiology Part A: Molecular and Integrative Physiology*, **134**(4), 847-862.
- Evans, P.G.H. (2020) *European Whales, Dolphins, and Porpoises. Marine Mammal Conservation in Practice*, Academic Press, London and San Diego.
- Evans, P.G.H. and Bjørge, A. (2013) Marine mammals. *MCCIP Science Review*, 2013, 134–148.
- Evans, P., and Waggitt, J. (2020) Impacts of climate change on marine mammals, relevant to the coastal and marine environment around the UK. *MCCIP Science Review*, 2020, 421-455.
- Fire, S.E. and Van Dolah, F.M. (2012) Marine Biotoxins: Emergence of Harmful Algal Blooms as Health Threats to Marine Wildlife. In *New Directions in Conservation Medicine: Applied Cases in Ecological Health* (eds Aguirre, A.A., Ostfield, R.S. and Daszak P. ). Oxford University Press, New York, pp. 374–389.
- Forcada, J., Trathan, P.N. and Murphy, E.J. (2008) Life history buffering in Antarctic mammals and birds against changing patterns of climate and environmental variation. *Global Change Biology*, **14**(11), 2473-2488.
- Geraci, J. and Lounsbury, V. (2002) Marine mammal health, holding the balance in an ever changing sea. In *Marine Mammals – Biology and Conservation* (eds Evans, P.G.H. and Raga, J.A. ). Kluwer Academic/Plenum Publishers, New York, pp. 365–384.
- Gómez-Campos, E., Borrell, A. and Aguilar, A. (2011) Assessment of nutritional condition indices across reproductive states in the striped dolphin (*Stenella coeruleoalba*). *Journal of Experimental Marine Biology and Ecology*, **405**(1-2), 18-24.
- Goutte, A., Antoine, E., Weimerskirch, H. and Chastel, O. (2010) Age and the timing of breeding in a long-lived bird: a role for stress hormones? *Functional Ecology*, **24**(5), 1007-1016.
- Grady, J.M., Maitner, B.S., Winter, A.S., Kaschner, K., Tittensor, D.P., Record, S., Smith, F.A., Wilson, A.M., Dell, A.I., Zarnetske, P.L. and Wearing, H.J. (2019) Metabolic asymmetry and the global diversity of marine predators. *Science*, **363**(6425), p.eaat4220.
- Grebmeier, J.M. and Harrison, N.M. (1992) Seabird feeding on benthic amphipods facilitated by gray whale activity in the northern Bering Sea. *Marine Ecology Progress Series*, 125-133.
- Gulland, F.M.D. and Hall, A.J. (2007) Is marine mammal health deteriorating? *EcoHealth*, **4**, 135–150.
- Gutierrez-Munoz, P., Walters, A.E., Dolman, S.J. and Pierce, G.J., (2021) Patterns and trends in cetacean occurrence revealed by Shorewatch, a land-based citizen science program in Scotland (United Kingdom). *Frontiers In Marine Science*, **8**, 642386.
- Hammond, P.S., Berggren, P., Benke, H., Borchers, D.L., Collet, A., Heide-Jørgensen, M.P., Heimlich, S., Hiby, A.R., Leopold, M.F. and Øien, N. (2002) Abundance of harbour porpoise and other cetaceans in the North Sea and adjacent waters. *Journal of Applied Ecology*, **39**, 361–376.
- Hammond, P.S., Bearzi, G., Bjørge, A., Forney, K., Karczmarski, L., Kasuya, T., Perrin, W.F., Scott, M.D., Wang, J.Y., Wells, R.S. and Wilson, B. (2008) Phocoena. The IUCN Red List of Threatened Species 2008, e. T17027A6734992.
- Hammond, P.S., Macleod, K., Berggren, P., Borchers, D.L., Burt, L. *et al.* (2013) Cetacean abundance and distribution in European Atlantic shelf waters to inform conservation and management. *Biological Conservation*, **164**, 107–122.
- Hammond, P.S., Lacey, C., Gilles, A., Viquerat, S., Börjesson, P., Herr, H., Macleod, K., Ridoux, V., Santos, M.B., Scheidat, M., Teilmann, J., Vingada, J., and Øien, N. (2021) Estimates of cetacean abundance in European Atlantic waters in summer 2016 from the SCANS-III aerial and shipboard surveys. Available at: [https://scans3.wp.st-andrews.ac.uk/files/2021/06/SCANS-III\\_design-based\\_estimates\\_final\\_report\\_revised\\_June\\_2021.pdf](https://scans3.wp.st-andrews.ac.uk/files/2021/06/SCANS-III_design-based_estimates_final_report_revised_June_2021.pdf)
- Häussermann, V., Gutstein, C.S., Bedington, M., Cassis, D., Olavarria, C., Dale, A.C., Valenzuela-Toro, A.M., Perez-Alvarez, M.J., Sepúlveda, H.H., McConnell, K.M., Horwitz, F.E. and Försterra, G. (2017) Largest baleen whale mass mortality during strong El Niño event is likely related to harmful toxic algal bloom. *PeerJ*, **5**, e3123.
- Holt, J., Wakelin, S., Lowe, J. and Tinker, J. (2010) The potential impacts of climate change on the hydrography of the northwest European continental shelf. *Progress in Oceanography*, **86**(3-4), 361-379.
- Humphreys, M.P., Artioli, Y., Bakker, D.C.E., Hartman, S.E., León, P., Wakelin, S., Walsham, P. and Williamson, P. (2020) Air–sea CO<sub>2</sub> exchange and ocean acidification in UK seas and adjacent waters, *MCCIP Science Review*, 2020, 54-75.
- ICES (2021). Working Group on Marine Mammal Ecology (WGMME). *ICES Scientific Reports*, **3**(19), 155 pp.
- IPCC (2021) Summary for Policymakers. In *Climate Change 2021: The Physical Science Basis*. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change (eds V. Masson-Delmotte, P. Zhai, A. Pirani, S.L. Connors, C. Péan, S. Berger, N. Caud *et al.* eds.). Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 3–32. doi:10.1017/9781009157896.001.

- Jansen, O.E., Leopold, M.F., Meesters, E.H. and Smeenk, C. (2010) Are white-beaked dolphins *Lagenorhynchus albirostris* food specialists? Their diet in the southern North Sea. *Journal of the Marine Biological Association of the United Kingdom*, **90**(8), 1501-1508.
- Johnson, C., Reisinger, R., Palacios, D., Friedlaender, A., Zerbini, A., Willson, A., Lancaster, M., Battle, J., Graham, A., Cosandey-Godin, A., Jacob T., Felix, F., Shahid, U., Houtman, N., Alberini, A., Montecinos, Y., Najera, E. and Kelez, S. (2022) Protecting Blue Corridors, Challenges and Solutions for Migratory Whales Navigating International and National Seas. WWF, Oregon State University, University of California, Santa Cruz, Publisher: WWF International, Switzerland.
- Josey, S.A., Hirschi, J.J.M., Sinha, B., Duchez, A., Grist, J.P. and Marsh, R. (2018). The recent Atlantic cold anomaly: Causes, consequences, and related phenomena. *Annual Review of Marine Science*, **10**, 475-501.
- Kaschner, K., Tittensor, D.P., Ready, J., Gerrodette, T. and Worm, B. (2011) Current and future patterns of global marine mammal biodiversity. *PLoS ONE*, **6**(5), e19653.
- Kebke, A., Samarra, F. and Derous, D. (2022) Climate change and cetacean health: impacts and future directions. *Philosophical Transactions of the Royal Society B*, **377**(1854), 20210249.
- Kershaw, J.L., Ramp, C.A., Sears, R., Plourde, S., Brosset, P., Miller, P.J. and Hall, A.J. (2021) Declining reproductive success in the Gulf of St. Lawrence's humpback whales (*Megaptera novaeangliae*) reflects ecosystem shifts on their feeding grounds. *Global Change Biology*, **27**(5), 1027-1041.
- Kiszka, J.J., Heithaus, M.R. and Wirsing, A.J. (2015) Behavioural drivers of the ecological roles and importance of marine mammals. *Marine Ecology Progress Series*, **523**, 267-281.
- Knowlton, A.R., Kraus, S.D. and Kenney, R.D. (1994) Reproduction in North Atlantic right whales (*Eubalaena glacialis*). *Canadian Journal of Zoology*, **72**(7), 1297-1305.
- Lafferty, K.D. and Holt, R.D. (2003). How should environmental stress affect the population dynamics of disease? *Ecology Letters*, **6**(7), 654-664.
- Laidre, K.L., Stern, H., Kovacs, K.M., Lowry, L., Moore, S.E. et al. (2015) Arctic marine mammal population status, sea ice habitat loss, and conservation recommendations for the 21st century. *Conservation Biology*, **29**(3), 724-737.
- Laidre, K.L., Stirling, I., Lowry, L.F., Wiig, Ø., Heide-Jørgensen, M.P. and Ferguson, S.H. (2008) Quantifying the sensitivity of Arctic marine mammals to climate-induced habitat change. *Ecological Applications*, **18**(sp2), S97-S125.
- Le Boeuf, B., Condit, R. and Reiter, J. (2019) Lifetime reproductive success of northern elephant seals (*Mirounga angustirostris*). *Canadian Journal of Zoology*, **97**(12), 1203-1217.
- Lohrengel, K., Evans, P.G.H., Lindenbaum, C.P., Morris, C.W. and Stringell, T.B. (2018) Bottlenose Dolphin Monitoring in Cardigan Bay 2014-2016, NRW Evidence Report No: 191, 162 pp.
- Matthews, C.J., Breed, G.A., LeBlanc, B. and Ferguson, S.H. (2020) Killer whale presence drives bowhead whale selection for sea ice in Arctic seascapes of fear. *Proceedings of the National Academy of Sciences*, **117**(12), 6590-6598.
- McClintock, B.T., Russell, D.J., Matthiopoulos, J. and King, R. (2013) Combining individual animal movement and ancillary biotelemetry data to investigate population-level activity budgets. *Ecology*, **94**(4), 838-849.
- Miller, C.A., Reeb, D., Best, P.B., Knowlton, A.R., Brown, M.W. and Moore, M.J. (2011) Blubber thickness in right whales *Eubalaena glacialis* and *Eubalaena australis* related with reproduction, life history status and prey abundance. *Marine Ecology Progress Series*, **438**, 267-283.
- Morgan, L.H., Morris, C.W., and Stringell, T.B. (2018) Grey Seal Pupping Phenology on Ynys Dewi/Ramsey Island, Pembrokeshire. NRW Evidence Report No: 156, 22 pp.
- Moore, S.E. (2016) Is it 'boom times' for baleen whales in the Pacific Arctic region? *Biology Letters*, **12**, 20160251.
- Moore, S. and Reeves, R.R. (2018) Tracking arctic marine mammal resilience in an era of rapid ecosystem alteration. *PLoS Biology*, **16**(10).
- Morris, C.D. and Duck, C.D. (2019) Aerial thermal-imaging surveys of harbour and grey seals in Northern Ireland, August 2018.
- Nøttestad, L., Krafft, B.A., Anthonypillai, V., Bernasconi, M., Langård, L., Mørk, H.L. and Ferno, A. (2015) Recent changes in distribution and relative abundance of cetaceans in the Norwegian Sea and their relationship with potential prey. *Frontiers in Ecology and Evolution*, **3**, 29.
- Ó Cadhla, O., Keena, T., Strong, D., Duck, C. and Hiby L. (2013) Monitoring of the breeding population of grey seals in Ireland, 2009-2012. *Irish Wildlife Manuals*, **74**, 18 pp.
- Patz, J.A., Daszak, P., Tabor, G.M., Aguirre, A.A., Pearl, M., Epstein, J., Wolfe, N.D., Kilpatrick, A.M., Fofopoulou, J., Molyneux, D. and Bradley, D.J. (2004) Unhealthy landscapes: policy recommendations on land use change and infectious disease emergence. *Environmental Health Perspectives*, **112**(10), 1092-1098.
- Paxton, C.G.M., Scott-Hayward, L., Mackenzie, M., Rexstad, E. and Thomas, L. (2016) Revised Phase III Data Analysis of Joint Cetacean Protocol Data Resources. JNCC Report No. 517, JNCC, Peterborough.

- Peperzak, L. (2003) Climate change and harmful algal blooms in the North Sea. *Acta Oecologica*, **24**, (Supplement 1), 139–144.
- Pinnegar, J.K. and Heath, M. (2010) Fish in MCCIP Annual Report Card 2010-11, *MCCIP Science Review* 2010, 23pp
- Pinsky, M.L., Eikeset, A.M., McCauley, D.J., Payne, J.L. and Sunday, J.M. (2019) Greater vulnerability to warming of marine versus terrestrial ectotherms. *Nature*, **569**(7754), 108-111.
- Poloczanska, E.S., Brown, C.J., Sydeman, W.J., Kiessling, W., Schoeman, D.S., Moore, P.J., Brander, K., Bruno, J.F., Buckley, L.B., Burrows, M.T. and Duarte, C.M. (2013) Global imprint of climate change on marine life. *Nature Climate Change*, **3**(10), 919-925.
- Ramp, C., Delarue, J., Palsbøll, P.J., Sears, R. and Hammond, P.S. (2015) Adapting to a warmer ocean – seasonal shift of baleen whale movements over three decades. *PLoS One*, **10**(3), e0121374.
- Rice, E., Dam, H.G. and Stewart, G. (2015). Impact of climate change on estuarine zooplankton: surface water warming in Long Island Sound is associated with changes in copepod size and community structure. *Estuaries and coasts*, **38**(1), 13-23.
- Roman, J., Estes, J.A., Morissette, L., Smith, C., Costa, D., McCarthy, J., Nation, J.B., Nicol, S., Pershing, A. and Smetacek, V. (2014) Whales as marine ecosystem engineers. *Frontiers in Ecology and the Environment*, **12**(7), 377-385.
- Sadykova, D., Scott, B.E., De Dominicis, M., Wakelin, S.L., Wolf, J. and Sadykov, A. (2020) Ecological costs of climate change on marine predator–prey population distributions by 2050. *Ecology and evolution*, **10**(2), 1069-1086.
- Sanderson, C.E. and Alexander, K.A. (2020) Uncharted waters: Climate change likely to intensify infectious disease outbreaks causing mass mortality events in marine mammals. *Global Change Biology*, **26**(8), 4284-4301.
- Santos, M.B. and Pierce, G.J. (2003) The diet of harbour porpoise (*Phocoena phocoena*) in the northeast Atlantic: A review. *Oceanography and Marine Biology, An Annual Review*, **41**, 363-369.
- Scholin, C.A., Gulland, F., Doucette, G.J., Benson, S., Busman, M., Chavez, F.P., Cordaro, J., DeLong, R., De Vogelaere, A., Harvey, J. and Haulena, M. (2000). Mortality of sea lions along the central California coast linked to a toxic diatom bloom. *Nature*, **403**(6765), pp.80-84.
- SCOS (Special Committee on Seals) (2018) Scientific Advice on Matters Related to the Management of Seal Populations: 2018. UK SCOS Annual Report, Sea Mammal Research Unit, University of St Andrews, 155 pp.
- SCOS (Special Committee on Seals) (2021) Scientific Advice on Matters Related to the Management of Seal Populations: 2021. UK SCOS Annual Report, Sea Mammal Research Unit, University of St Andrews.
- Serpetti, N., Baudron, A.R., Burrows, M.T., Payne, B.L., Helaouet, P., Fernandes, P.G. and Heymans, J.J. (2017) Impact of ocean warming on sustainable fisheries management informs the Ecosystem Approach to Fisheries. *Scientific reports*, **7**(1), 1-15.
- Sheehy, J.M., Taylor, N.L., Zwerschke, N., Collar, M., Morgan, V. and Merayo, E. (2022). Review of evaluation and valuation methods for cetacean regulation and maintenance ecosystem services with the joint cetacean protocol data. *Frontiers in Marine Science*, **9**, 872679.
- Siano, R., Chapelle, A., Antoine, V., Michel-Guillou, E., Rigaut-Jalabert, F., Guillou, L., Hegaret, H., Leynaert, A. and Curd, A. (2020) Citizen participation in monitoring phytoplankton seawater discolorations. *Marine Policy*, **117**, 103039.
- Simeone, C.A., Gulland, F.M.D., Norris, T. and Rowles, T.K. (2015) A Systematic Review of Changes in Marine Mammal Health in North America, 1972–2012: The Need for a Novel Integrated Approach. *PLoS ONE*, **10**(11), e0142105.
- Simmonds, M.P. and Isaac, S.J. (2007) The impacts of climate change on marine mammals: early signs of significant problems. *Oryx*, **41**(1), 19-26.
- Smit, T., Lemley, D.A., Adams, J.B. and Strydom, N.A. (2021). Preliminary insights on the fine-scale responses in larval *Gilchristella aestuaria* (Family Clupeidae) and dominant zooplankton to estuarine harmful algal blooms. *Estuarine, Coastal and Shelf Science*, **249**, p.107072.
- Smout, S., King, R. and Pomeroy, P. (2020) Environment-sensitive mass changes influence breeding frequency in a capital breeding marine top predator. *Journal of Animal Ecology*, **89**(2), 384-396.
- Sonnewald, M. and Lguensat, R. (2021) Revealing the impact of global heating on North Atlantic circulation using transparent machine learning. *Journal of Advances in Modeling Earth Systems*, **13**(8), p.e2021MS002496.
- Søreide, J.E., Leu, E.V., Berge, J., Graeve, M. and Falk-Petersen, S.T.I.G. (2010) Timing of blooms, algal food quality and *Calanus glacialis* reproduction and growth in a changing Arctic. *Global change biology*, **16**(11), 3154-3163.
- Sorte, C.J., Williams, S.L. and Carlton, J.T. (2010) Marine range shifts and species introductions: comparative spread rates and community impacts. *Global Ecology and Biogeography*, **19**(3), 303-316.
- Stearns, S. (1992). *The Evolution of Life Histories*. New York, NY: Oxford University Press.
- Stirling, I. and Derocher, A.E. (2012) Effects of climate warming on polar bears: a review of the evidence. *Global Change Biology*, **18**(9), 2694-2706.

- Strand, E., Bagoien, E., Edwards, M., Broms, C. and Klevjer, T. (2020) Spatial distributions and seasonality of four *Calanus* species in the Northeast Atlantic. *Progress in Oceanography*, **185**, 102344.
- Studer, A., Thielges, D.W. and Poulin, R. (2010) Parasites and global warming: net effects of temperature on an intertidal host–parasite system. *Marine Ecology Progress Series*, **415**, 11–22.
- Sydeman, W.J., Poloczanska, E., Reed, T.E. and Thompson, S.A. (2015) Climate change and marine vertebrates. *Science*, **350**(6262), 772–777.
- Thorne, L.H. and Nye, J.A. (2021) Trait-mediated shifts and climate velocity decouple an endothermic marine predator and its ectothermic prey. *Scientific Reports*, **11**(1), 1–14.
- Tinker, J.P. and Howes, E.L. (2020) The impacts of climate change on temperature (air and sea), relevant to the coastal and marine environment around the UK. *MCCIP Science Review*, 2020, pp. 1–30.
- Tracy, A.M., Pielmeier, M.L., Yoshioka, R.M., Heron, S.F. and Harvell, C.D. (2019) Increases and decreases in marine disease reports in an era of global change. *Proceedings of the Royal Society B*, **286**(1912), 20191718.
- Trifonova, N., Scott, B., De Dominicis, M. and Wolf, J. (2022) Use of our future seas: Relevance of spatial and temporal scale for physical and biological indicators. *Frontiers in Marine Science*, **8**, 769680.
- Van Bresseem, M-F, Raga, J.A., Di Guardo, G., Jepson P.D., Duignan, P.J. *et al.* (2009) Emerging infectious diseases in cetaceans worldwide and the possible role of environmental stressors. *Diseases of Aquatic Organisms*, **86**, 143–157.
- van Deurs, M., van Hal, R., Tomczak, M.T., Jónasdóttir, S.H. and Dolmer, P. (2009) Recruitment of lesser sandeel *Ammodytes marinus* in relation to density dependence and zooplankton composition. *Marine Ecology Progress Series*, **381**, 249–258.
- Van Dolah, F.M. (2000) Marine algal toxins, origins, health effects, and their increased occurrence. *Environmental Health Perspectives*, **108** (Suppl.), 133–141.
- Vikingsson, G.A., Pike, D.G., Valdimarsson, H., Schleimar, A., Gunnlaugsson, T., Silva, T., Elvarsson, B.P., Mikkelsen, B., Øien, N., Desportes, G., Bogason, V. and Hammond, P.S. (2015) Distribution, abundance, and feeding ecology of baleen whales in Icelandic waters: have recent environmental changes had an effect? *Frontiers in Ecology and Evolution*, **3**, 29.
- von Hammerstein, H., Setter, R.O., van Aswegen, M., Currie, J.J. and Stack, S.H. (2022) High-resolution projections of global sea surface temperatures reveal critical warming in humpback whale breeding grounds. *Frontiers in Marine Science*, **9**, 837772.
- Wakelin, S.L., Artioli, Y., Holt, J.T., Butenschön, M. and Blackford, J. (2020) Controls on near-bed oxygen concentration on the Northwest European Continental Shelf under a potential future climate scenario. *Progress in Oceanography*, **187**, p.102400.
- Watson, S.C., Preston, J., Beaumont, N.J. and Watson, G.J. (2020) Assessing the natural capital value of water quality and climate regulation in temperate marine systems using a EUNIS biotope classification approach. *Science of the Total Environment*, **744**, p.140688.
- Weir, C.R., Macleod, C.D. and Calderan, S.V. (2009) Fine-scale habitat selection by white-beaked and common dolphins in the Minch (Scotland, UK): evidence for interspecific competition or coexistence? *Journal of the Marine Biological Association of the United Kingdom*, **89**(5), 951–960.
- Whitehead, H., McGill, B. and Worm, B. (2008) Diversity of deep-water cetaceans in relation to temperature, implications for ocean warming. *Ecology Letters*, **11**, 1198–1207.
- Wild, S., Krützen, M., Rankin, R.W., Hoppitt, W.J., Gerber, L. and Allen, S.J. (2019) Long-term decline in survival and reproduction of dolphins following a marine heatwave. *Current Biology*, **29**(7), R239–R240.
- Williamson, M.J., ten Doeschate, M.T., Deaville, R., Brownlow, A.C. and Taylor, N.L. (2021) Cetaceans as sentinels for informing climate change policy in UK waters. *Marine Policy*, **131**, 104634.
- Willoughby, A.L., Ferguson, M.C., Stimmelmayer, R., Clarke, J.T. and Brower, A.A. (2020) Bowhead whale (*Balaena mysticetus*) and killer whale (*Orcinus orca*) co-occurrence in the US Pacific Arctic, 2009–2018: evidence from bowhead whale carcasses. *Polar Biology*, **43**(11), 1669–1679.
- Wright, P.J., Pinnegar, J.K. and Fox, C. (2020) Impacts of climate change on fish, relevant to the coastal and marine environment around the UK. *MCCIP Science Review*, 2020, 354–381.