The Impacts of Climate Change on shallow subtidal, shelf and deep-sea habitats relevant to the coastal and marine environment around the UK and Ireland

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KEY FACTS

What is already happening?

- North Sea infaunal (burrowing) species have shifted their distributions in response to changing sea temperature, however, most species have not been able to keep pace with shifting temperature, meaning that species are subjected to warmer conditions. Leading (expanding) edges are responding more quickly than trailing (retreating) edges, which has been observed elsewhere in the world.
- Changes in the relative abundance of several UK kelp species, linked to sea-temperature rise, is leading to alterations in the structure of kelp forest assemblages. This has implications for kelp-forest community structure and habitat resilience.
- Changes in phytoplankton and zooplankton communities attributable to climate change impacts affecting primary production directly alter the flux of Particulate Organic Carbon (POC) to the seabed, therefore reducing food supply to deep-sea organisms.
- Deep-sea sponge communities have shown resilience to changes in prevailing environmental conditions, therefore may be more adapted to climate change, however the impact of ocean acidification on calcareous and siliceous sponges is poorly understood.

What could happen in the future?

- Modelling suggests that there will be significant shifts in range, distribution and abundance of kelp across the UK by 2050, under low (Representative Concentration Pathways of greenhouse gases,

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RCP, 2.6), moderate (RCP 4.5) or high (RCP 8.5) emission scenarios in the future, altering the structure, functioning and ecosystem services provided by kelp forests.

- Modelling of climate-change impacts on benthic infauna and epifauna within the North Sea also shows altered community structures under a range of emission scenarios by end of century. Such changes are likely to have implications for food-web dynamics, fisheries, carbon cycling and ultimately human society.
- Changes in temperature and pH could lead to increased mortality of the reef forming *Desmophyllum pertusum* in situ. Lower pH also increases the dissolution of dead coral framework thereby breaking down the reef infrastructure.
- Projections to end of the century conditions have predicted a severe decline in habitat suitability for cold-water corals, for example *D. pertusum* might see the largest decline in suitable habitat with only 30 to 42% of present-day habitat persisting as climate refugia.
- Global and regional predictions demonstrate that UK deep-sea sediment habitats could be adversely affected by the impact of climate change in terms of primary production, by 2100. Under emissions scenarios RCP 4.5 and 8.5, global declines in seafloor biomass are projected to be <1% by the year 2020, declining by 3% by 2050 and 5.9% by the year 2080.

SUPPORTING EVIDENCE

Introduction

Shallow and shelf subtidal habitats and the communities of species that occupy them are an essential component of the UK’s marine ecosystem. These habitats are mainly sedimentary; sediment composition varies depending on tidal regime, wave action and sediment supply. The most species-rich sediments are those that are stable over time and a community may contain over 200 species per square metre (Hiscock, 1996). Shallower depths can be dominated by hard substrata, mainly rocky habitats, characterised by rich kelp forests in the well-lit waters which give way to animal-dominated communities in deeper circalittoral zones supporting a plethora of sessile species. Deep-sea habitats are classified as being below 200 m water depth, or those beyond the continental shelf break. In UK waters, the maximum depth of deep-sea habitats is over 4000 m, located in the Southwest Canyons. A wide diversity of deep seafloor habitats and geological features occurs in UK waters, including submarine canyons, seamounts, cold-water coral reefs and gardens, sponge aggregations and soft-sediment habitats. These support diverse communities of invertebrates. Our knowledge of deep-sea habitats is still limited in relation to the extensive area of unexplored UK waters.

Shallow, shelf and deep-sea habitats and their associated communities are an integral part of a healthy ocean and provide valuable ‘ecosystem services’. In UK waters, such communities support the production of food, climate regulation, flood protection, pollution sinks and recreational and aesthetic benefits (Fletcher *et al*., 2012). For example, sublittoral sediment communities can provide important nursery grounds for juvenile commercial species such as flatfishes and bass. Offshore, sand and gravel habitats support internationally important fish and shellfish fisheries (BRIG, 2011). Cold-water corals in the North-East Atlantic provide important habitats for fish (Costello *et al*., 2005; Milligan *et al*., 2016) and are important reservoirs for – and hotspots of – deep-sea biodiversity. Changes to shallow, shelf and deep-sea habitats resulting from climate-change impacts will likely alter the ecosystem services currently provided.

This report focuses on the key species and communities occurring below low water that are demonstrating ecological responses to changes in sea conditions driven by climate change. These include kelps, infaunal communities, cold-water coral reefs and gardens and deep-sea sponge communities. These communities are classified as ‘threatened and declining’ habitats under OSPAR (2023). They exclude seagrass beds, which are covered by Marsh *et al*. (2026).

Summary of the main physical conditions driving change in the shallow, shelf and deep seas

2024 was the warmest year on record in relation to global temperatures recorded since records began in 1850. 2024 had a global average temperature of 15.10°C; 0.12°C higher than the previous highest annual value in 2023 (Copernicus Climate Service C3S). For 2024, the annual average extra-polar sea surface temperature (SST) was the highest on record, at 20.87°C, 0.51°C above the 1991–2020 average, surpassing the previous records of 2023 (20.80°C) and 2016 (20.61°C). Global SST in March 2024 was the highest monthly value on record (Figure 1). Changes in SST can alter marine ecosystems in several ways.

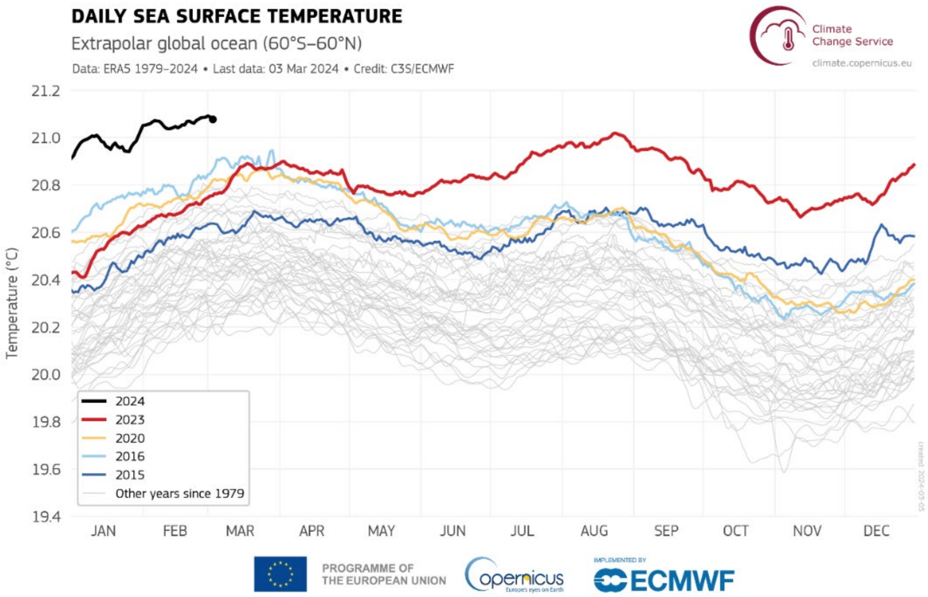


Figure 1. *Daily global sea surface temperatures (SSTs) excluding the polar regions showing March 2024 as the warmest global SSTs on record.*

Marine Heat Waves (MHWs) are periods of extreme high sea temperature relative to the long-term mean seasonal cycle. While negative impacts on individual species and communities cannot be ruled out, to date there has been no observed impact of altered ocean chemistry in UK shelf waters. MHWs have also recently been shown to be a key driver of species range shifts (Wernberg *et al*., 2016; Oliver *et al*., 2018). Biological responses to MHWs occur at the individual, population and community levels and typically intensify toward the warm trailing range edges of species distributions (Smith *et al*., 2023).

Multiple environmental variables influence deep-sea habitats, which may be further affected by climate change in the future. Particularly relevant to deep-sea habitats in the UK are: (1) temperature, (2) oxygen, (3) pH, (4) hydrographic features and (5) primary production in the surface waters (Sweetman *et al*., 2017). Changes in these environmental variables will likely affect viable larval recruitment, population dynamics, community structure and ecosystem functioning.

The Atlantic meridional overturning circulation (AMOC) is the system of water currents that drives warm surface water northwards and cold, deep waters back southwards within the Atlantic basin. In addition, it is the main source of oxygen for deep-water ecosystems. Decadal variability in the boundary between subpolar and subtropical waters has caused changes in the proportion of these water masses in the Iceland and Rockall basins, with a greater influence of warm subtropical waters (Spooner *et al*., 2020). The changing subpolar ocean circulation is also having impacts on deep-sea food supply (McCarthy *et al*. 2023). Temperature in the deep sea has shown no clear trends. In deeper water of the Faroe-Shetland channel (below 1100 m) there was a declining trend in temperatures from the 1950s to the 1990s. Since the 2000s through to the early 2020s an increasing trend is evident (Cornes *et al*., 2023). Upper ocean waters in the Rockall Trough to the west of the UK (30–800 m), display a similar decadal pattern to the Faroe-Shetland Channel to the north of the UK with a period of elevated temperatures during the mid-2000s, declining thereafter (Cornes *et al*., 2023). The combination of increasing SST and freshwater input from melting sea ice intensifies stratification in the surface waters and is weakening the AMOC (Defrance *et al*., 2017).

Increasing SST also impacts deep-sea ecosystems, by decreasing oxygen solubility and impacting hydrographic features. As warming increases stratification, vertical mixing lessens and oxygenated water cannot be transported, creating deoxygenation zones below 1000 m which will further impact conditions for deep sea life to survive. Decreasing ocean pH due to increased CO2 creates problems for organisms that have hard exoskeletons of calcium carbonate such as cold-water corals and crustaceans, by dissolving their skeletons and therefore reducing their abundance.

In the North-East Atlantic, shifts in phytoplankton community composition, abundance and distribution have been revealed by the Continuous Plankton Recorder surveys (Beaugrand 2009; Hinder *et al*., 2012; Rivero-Calle *et al*., 2015; Martinez *et al*., 2016). These shifts in phytoplankton have been coupled to shifts in community composition, abundance and distribution of zooplankton and higher trophic levels, for example fish, linked to increased temperatures (Beaugrand 2009; Hátún *et al*., 2009). Changes in phytoplankton and zooplankton communities will directly affect the flux of Particulate Organic Carbon (POC) through the water column to the deep-sea floor, potentially reducing food availability for filter feeding and deposit feeding invertebrates.

WHAT IS ALREADY HAPPENING?

Sublittoral and deep-sea sediment

Pelagic primary production reveals climatic influence (Behrenfeld *et al*., 2006; Blanchard *et al*., 2012; Boyce *et al*., 2010;), with some studies, at a global scale, suggesting increased SST will lead to reduced primary productivity (Behrenfeld *et al*., 2006). At a regional scale the patterns are more complex, but for much of the British Isles, except for the west coasts of Ireland and Scotland, a negative relationship between increasing SST and primary productivity has been observed (Dunstan *et al*., 2018). Such a reduction in primary productivity with increased SST is therefore likely to lead to food shortages for smaller bodied infauna and increased community fluctuations.

As each species responds differently to climate change pressures, this will ultimately change how overall communities are structured. Clare *et al*. (2017) analysed data from the Dove Time Series (1972–2012) to investigate the influence of changes in SST and primary productivity (a proxy for food availability) on benthic community structure. In general, large, long-lived fauna experienced changes in relative abundance concordant with changes in food availability. Increased detrital production allowed species that were food limited to increase in abundance and out compete species that had lower energy requirements leading to the observed changes (Clare *et al*., 2017). Small, generally shorter-lived fauna experienced some changes in community structure related to changes in SST, but this effect was dampened as food availability increased (Clare *et al*., 2017). Increased food availability nullified the effect of increased temperatures because there was sufficient food to meet the increased metabolic demands associated with increased temperatures.

Hiddink *et al*. (2015) examined geographical and bathymetric shifts of 65 benthic infaunal invertebrates in the North Sea comparing distributions in 1986 with those of 2000. They found temperatures had increased throughout the North Sea coinciding with a north-westerly shift (range-centre, leading and trailing edge) and deepening of many species' ranges. Leading edges expanded faster than trailing edges (Hiddink *et al*., 2015), which has also been noted in global-scale analyses (Poloczanska *et al*., 2013).

In the Western English Channel, one study compared benthic communities sampled in 1958/59 with those sampled in 2006 and found no broad-scale temporal differences related to warming, although four warm-water affinity species were detected in the later survey, but not in the earlier one (Hinz *et al*., 2011). The authors suggest this could have been in response to climate warming (Hinz *et al*., 2011). More recently, Navarro-Barranco *et al*. (2017) investigated changes in amphipod assemblages between 2008–2014 at station L4, which forms part of the Western Channel Observatory (www.westernchannelobservatory.org.uk) and is one of the best studied marine areas in Europe. Amphipod abundance, richness and community structure were influenced by seasonal and year-to-year variability, however, increased Sea Bottom Temperature (SBT) resulted in a significant increase in amphipod abundance and richness with this environmental driver accounting for 57% and 23% of the variability in abundance and richness, respectfully (Navarro-Barranco *et al*., 2017).

Although not a UK deep-sea habitat, the Porcupine Abyssal Plain (PAP) Sustained Observatory in the mid-Atlantic, approximately 500 km west of Ireland, has focussed on the study of connectivity between the surface and seabed. In-situ measurements of climatically and environmentally relevant variables have been made for more than 30 years (Hartman *et al*., 2021). Soft sediment community changes in the PAP have been attributed to variation in the quantity and quality of food supplied to the community via supply of POC, with changes in climate suggested as the contributing factor (Billett *et al*., 2001; Hudson *et al*., 2003). Changes in megafauna recruitment, immigration, emigration and mortality related to climate-induced variations in food supply could explain this (Ruhl and Smith, 2004; Horton *et al*., 2020).

Changes in seafloor community structure are likely to have consequences for carbon cycling and organic matter remineralisation, for example, at the PAP during a period when megafaunal densities were high, the surface sediment was turned over in less than four months (Ginger *et al*., 2001).

Sublittoral rock and hard substrata

Yesson *et al*. (2015) collated and analysed data on changes in large UK brown algal abundance. At the UK scale, *Chorda filum*, *Laminaria ochroleuca*, *Saccharina latissima* all reduced in abundance, however, for the warm-water species, *L. ochroleuca*, this was not related to changes in temperature. Four kelp species showed significant relationships between abundance patterns and SST with *C. filum* abundance positively correlated with winter SST whereas *L. digitata*, *L. hyperborea* and *S. latissima* abundance was negatively correlated with winter SST. Interestingly, for the cold-water species*, L. digitata* and *L. hyperborea*, abundance was positively correlated with summer SST. Abundance also varied across regions with a general pattern of relative stability or increased abundance through time in northern regions (Scotland, northern England) and a reduction in abundance in southern regions (south-west England). It should be noted that 74% of site-level studies were based on just two time points with only 3% of sites having four temporal observations for any species and therefore the data are better interpreted at a UK scale rather than regional. Results for kelp species from this study should therefore be interpreted with some caution.

The warm-water species*, L. ochrolueca*, reaches its northern range limit in the Western English Channel and Celtic Seas, while the cold-water species, *Alaria esculenta*, reaches its southern range limit in the same region with both species proposed as good indicators for climate-driven changes in abundance and distribution (Mieszkowska *et al*., 2006; Smale *et al*., 2014).

There has been an observed increase in the abundance of *L. ochroleuca* linked to increases in SST at sites around Plymouth, Isles of Scilly and Lundy Island, in some cases becoming the dominant species (Plymouth and Isles of Scilly) (Smale *et al*., 2014; Teagle and Smale, 2018).

Declines in abundance were also noted for *Saccorhiza polyschides* in the Western English Channel and Celtic Seas and *C. filum* and *L. hyperborea* in the English Channel (Yesson *et al*., 2015). While the decline in *S. polyschides* was not related to changes in SST at the UK scale, the declines in *L. hyperborea* and *C. filum* were correlated with SST (see above). While declines in the dominant intertidal/ shallow subtidal kelp *L. digitata* have not been observed in the UK, declines have been observed along the Brittany, Normandy and French English-Channel coasts which have been linked to harvesting pressures as well as climate change (Raybaud *et al*., 2013). Given that *L. digitata* found in south-west England occupies the same temperature isotherm as French populations (King *et al*., 2017) it is highly likely that *L. digitata* abundance will decline in the western English Channel in the near future.

Cold-water coral reefs and gardens

The cold-water coral *Desmophyllum pertusum* forms reefs which may be circular, dome-shaped or elongated, forming distinct patches or arranged in lines of 'islands' along the edges of the continental shelf, sea mounts, offshore banks and other raised seabed features, notably in Hatton Bank, Darwin Mounds and Mingulay reef in north-west Scotland and the Canyons in south-west England. In favourable environmental conditions, reefs can form long banks of coral up to 5 km in length and 1 km wide, reaching heights of 200 m covering several square kilometres. Cold-water coral reefs support a diverse range of other biota (Perry and Tyler-Walters, 2016). Coral gardens can comprise a range of coral types including hard/stony corals, soft corals, black corals, sea pens and gorgonians. Evidence of climate change impacts on coral gardens in UK waters and the North-East Atlantic more generally, is poor.

Laboratory studies have been used to investigate the impact of elevated temperature and lower pH on *D. pertusum*. They show that temperature and pH impact key physiological and metabolic processes including calcification but with the species possibly exhibiting some level of long-term acclimatisation to future conditions (Hennige *et al*., 2015; Büscher *et al*., 2017, 2022). Specifically, elevated temperature has been shown to increase *D. pertusum* calcification rate while acidification leads to a decrease (Hennige *et al*., 2015; Büscher *et al*., 2022). Effects of temperature could therefore mitigate effects of acidification, when food supply is not limited and higher coral energy demands can be met (Büscher *et al*., 2017, 2022; Chapron *et al*., 2021; Gomez *et al*., 2022). Mitigation of the physiological impacts of these two stressors is also likely to occur at the expense of other metabolic processes (Büscher *et al*., 2022). Furthermore *D. pertusum* exhibits limited capacity to enhance its feeding behaviour when food availability is temporarily high, contradictory to other coral species

(Büscher *et al*., 2017; Chapron *et al*., 2021; Gomez *et al*., 2022). This would indicate that the ability of *D. pertusum* to cope with changes in temperature and pH could lead to increased mortality in situ. In addition to the ocean acidification effects reported on live *D. pertusum* fragments or colonies, lower pH also increases the dissolution of dead coral framework (Hennige *et al*., 2015, 2020; Büscher *et al*., 2022; Wolfram *et al*., 2022; Krueger *et al*., 2023) and lead to the development of coralporosis, a weakening of the coral exoskeleton (Hennige *et al*., 2020).

While previous studies have found that low oxygen concentrations could be stressful for certain species of UK cold-water coral including for reef-forming *D. pertusum*, discoveries of thriving South-East Atlantic deep-sea coral reefs in hypoxic waters have somewhat modulated this perspective. Indeed, *D. pertusum* reefs discovered in the south-east Atlantic show that the coral species is able to thrive in hypoxic (and relatively warm) waters (Hebbeln *et al*., 2020). Therefore, *D. pertusum* seems to present a higher than previously expected tolerance to low oxygen conditions, partly due to the constant availability of large quantities of high-quality organic matter as food intake (Hebbeln *et al*., 2020). In addition, it is important to note that *D. pertusum* populations seem to have low adaptive capacities when exposed to a reduction in oxygen concentration (Dodds *et al*., 2007). Therefore, deoxygenation in UK waters in combination with other stressors should still be considered when investigating the impact of climate change on cold-water corals.

Adequate food supply could be crucial to allow deep-sea corals to maintain in changing seawater conditions. *D. pertusum* reefs have been estimated to require substantial amount of food derived from surface productivity (de Clippele *et al*., 2021; Maier *et al*., 2019, 2020, 2023). Yet, modelling studies have found changes in the amount and quality of surface productivity, ultimately impacting what is transported to the seabed (Sweetman *et al*., 2017). This would suggest the emergence of a ‘disbalanced energy budget’ in cold-water corals (Maier *et al*., 2023). Consideration of the seasonal variability in food supply to cold-water coral reefs also needs to encompass the impact of seasonality on *D. pertusum* and other coral species physiology and metabolism (van der Kaaden *et al*., 2021; Maier *et al*., 2021, 2023; De Froe *et al*., 2022) as well as the wider reef and coral garden composition (Kazanidis *et al*., 2021).

Deep-sea sponge aggregations

Overall, there is limited information about the impact of environmental change on deep-sea sponges. Sponges are often presented as potential winners of climate change and broadly expected to be more resilient than other benthic groups such as corals (Bennett *et al*., 2017; Bell *et al*., 2018; Scanes *et al*., 2018; Beazley *et al*., 2018, 2021). However, differences between species are significant with shallow-water species expected to be more robust to temperature fluctuations than deeper specimens (Guzman and Conaco, 2016; Carballo and Bell, 2017). Broadly temperature along with salinity and silica concentration has been found to drive sponge distribution the North-east Atlantic (Davison *et al*., 2019; Kazanidis *et al*., 2019; Burgos *et al*., 2020; Graves *et al*., 2023), hinting that deep-sea sponges are associated with specific water masses (Kazanidis *et al*., 2019; Puerta *et al*., 2020; Roberts *et al*., 2021). At small timescales, some deep-sea sponge grounds are known to experience large variation in temperature. In the Faroe-Shetland Channel for example, sponge grounds sit at a depth where temperature can change by up to 7°C within one hour (Bett, 2001; Kazanidis *et al*., 2019). Nevertheless, sponge mass-mortality events have been observed in Norway, potentially triggered by unusually warm temperatures (Guihen *et al*., 2012). Experimental work, however, suggests that deep-sea sponges can be resilient to temperature increase alone, showing signs of cellular and metabolic stress but not mortality and good recovery abilities (Strand *et al*., 2017).

The effect of ocean acidification on deep-sea sponges is poorly studied, with the assumption that (1) calcareous sponges will experience similar impacts to other calcifying organisms under acidified conditions and (2) most other species would be mostly resilient to decrease in pH due to their silica skeletons (Bell *et al*., 2018). This is confirmed on shallow-water species experimentally (Duckworth *et al*., 2012) and by studies that have examined organisms in the vicinity of natural CO_2 seeps (Morrow *et al*., 2015). However, decreased feeding rate has been identified in some deep-sea sponges exposed to lower pH (Robertson *et al*., 2017). Ocean acidification can impact silica flux from surface to deep waters (Petrou *et al*., 2019), leading to unclear effects on sponges, which rely on silica to build their skeletons (Maldonado *et al*., 2019, 2021).

Hindcast modelling studies have shown that deep-sea sponge grounds have persisted despite large variability in organic carbon flux to the sea floor (Samuelsen *et al*., 2022). This highlights a potential resilience of deep-sea sponge grounds to changes in food supply, possibly through the sponge loop, where sponges recycle organic matter into particulate detritus which acts as a food source (Bart *et al*., 2021). Sponge density across a shorter 18-year time-series study was shown to fluctuate with food supply at the seabed, highlighting that while assumed slow-growing, sponge populations are dynamic and respond to inter-annual changes (Kahn *et al*., 2012).

WHAT COULD HAPPEN IN THE FUTURE?

Sublittoral and deep-sea sediments

An Ecological Niche Model (ENM) based on IPCC SRES scenario A1B climate model (Nakicenovic and Swart, 2000; mean 2.8°C; range 1.7–4.4°C) was then used to predict the 2099 distribution of the 75 chosen species. The model predicted bottom temperature increases of 0.15–5.4°C across the North Sea with an increase in salinity of 1.7 in the northern North Sea and off the Dutch coast. For 18 (50%) of 36 epifaunal species the ENM predicted a northward range shift with the brittle star, *Ophiothrix fragilis*, predicted to shift up to 109 km and 65% of all epifaunal species investigated were predicted to shift their range between 10 and 50 km. A further 18 (50%) epifaunal species were predicted to shift southwards with 16 of the 18 species shifting in a south-easterly direction. The hermit crab, *Pagurus prideaux* and its associated cloak anemone, *Adamsia carciniopados* were predicted to shift southwards by 105 km, with 50% of all species predicted to shift 10–50 km. A greater number of infaunal species are expected to shift their distribution in a more-expected northward direction (77%). Shifts of 60 km or more were predicted for the bivalves *Nucula nitidosa* (60 km) and *Ennucula tenuis* (76 km), the brittle star *Acrocnida brachiata* (60 km), the amphipod *Harpinia antennaria* (75 km) and the mollusc *Chaetoderma nitidulum* (88 km). Overall, 60% of species were predicted to shift ranges by 10–50 km towards the north. Only 9% of infaunal species were predicted to shift range towards the south (Weinert *et al*., 2016). The potentially unexpected southward shifts particularly for epifauna, may be a consequence of regional conditions and other interacting affects (Junker *et al*., 2012; VanDerWal *et al*., 2012) as well as a key habitat barrier in the North Sea being the 50 m contour separating the shallow southern North Sea with the deeper northern North Sea. That may act as a barrier to northward extension of some species (Weinert *et al*., 2016).

In terms of changes in habitat space, 58% of epifauna and 72% of infauna were predicted to see a reduction in the availability of suitable habitat, while 38% of epifauna and 2% of infauna were expected to experience range expansion. Changes in community structure could alter ecosystem functioning and trophodynamics of North Sea benthic habitats. In turn this may impact important ecosystem services, for example biogeochemical processes, nutrient cycling, water quality and fisheries. The northward movement and therefore predicted loss of ecosystem engineers such as the burrowing shrimp *Callianassa subterranea* and the sea urchin *Brissopsis lyrifera* could alter community structure and ecosystem functioning (Weinert *et al*., 2016). At the same time, changes in the distribution and abundance of benthic communities may alter trophodynamics and competition (Kirby *et al*., 2007). However, such ecosystem-level responses will depend on the species involved, with some studies suggesting ecosystem functioning and service provision remaining stable over long periods of time (Frid and Caswell, 2015; Clare *et al*., 2015).

Projected changes in climate drivers will affect deep-seafloor sediment communities in ways that lead to range shifts (Brito-Morales *et al*., 2020), loss of suitable habitat (Morato *et al*., 2020), decreases in food availability and biomass (Jones *et al*., 2014) and ultimately biodiversity decrease (Levin *et al*., 2020).

Although predictions of the strength of decline in POC flux both through the water column and at the seafloor vary, the consensus is that POC flux to benthic habitats will decline under future climate simulations as increased stratification and slowed mixing reduces the nutrient supply for primary production at the ocean's surface and the reduction in POC flux will be the largest in the Atlantic Ocean, at depths relevant to UK deep-sea environments (Sweetman *et al*., 2017). Ultimately this will result in a reduction of food and chemical energy supply for deep-seafloor habitats (Jones *et al*., 2014; Yool *et al*., 2017). Reductions in POC flux to deep-sea habitats are likely to be exacerbated by the combined impacts of climate change which lead to increased freshwater input from melting sea ice and weakening circulatory systems (Kwiatkowski *et al*., 2019).

Declines in global seafloor biomass are predicted for the near future (2050) and end of century. Under Representative Concentration Pathways (RCP) emissions scenarios 4.5 and 8.5 (IPCC, 2014), global declines in seafloor biomass were projected to decline 4% by 2050 and 5.9% by the year 2080. In the North-East Atlantic, these projections are higher: a 19.5% decline in benthic biomass by 2090 is predicted under RCP 4.5 and by 38.5% under the RCP 8.5 (see Figure 2) (Jones *et al*., 2014). These global and regional predictions demonstrate that UK deep-sea habitats are likely to be adversely affected by the climate change impacts in terms of primary production, by 2100.

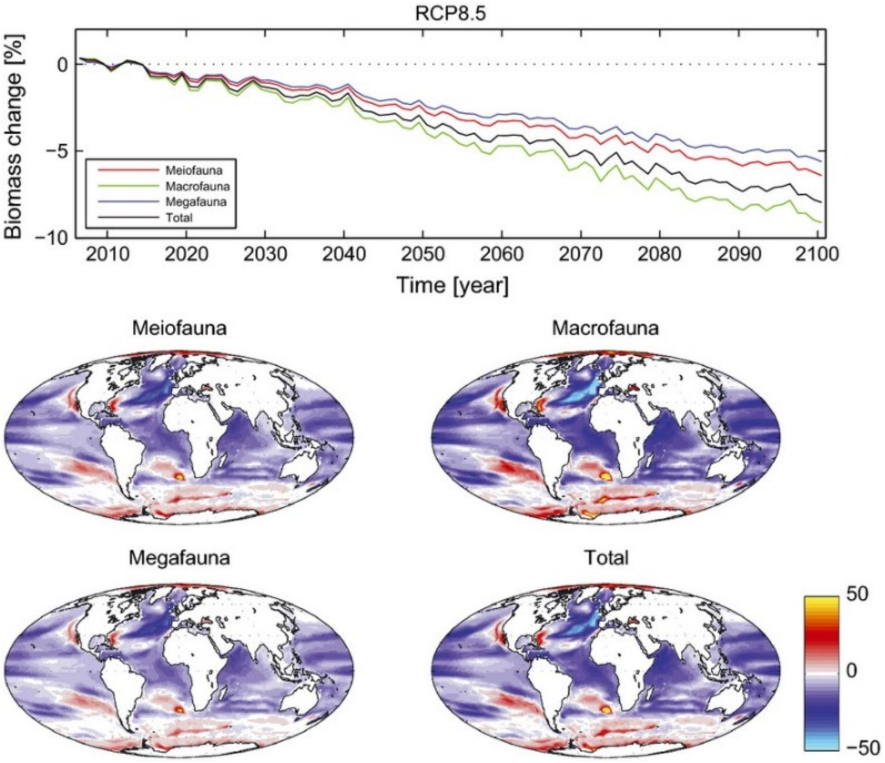


Figure 2. *Changes in benthic biomass between 2006–2015 and 2091–2100 under scenario RCP8.5. The graph shows projected changes in biomass of metazoan size-categories of benthos across the modelled time series (as annual means). The maps below show percentage changes in multi-model mean benthic biomass on seafloor (mg C m*$^{-2}$*). Benthic biomasses are presented as totals (metazoans only) and split into three size classes. (Source: Jones et al., 2014.)*

Sublittoral rock and hard substrata

ENMs provide predictions of changes in the abundance and distribution of European kelp species to future warming. Depending on the magnitude of warming their models suggest that there will be a reduction in the abundance of *L. digitata* across much of southern and central England and Wales (English Channel, Western English Channel, Celtic Seas and Irish Sea) with 50 to 100% of their model runs predicting loss of this species in parts of these regions by 2050 under RCP 2.6, 4.5 and 8.5 scenarios. By 2050 it is likely that Scottish populations will also have experienced a reduction in abundance, however, this species is likely to persist in Scotland beyond the end of the century (Raybaud *et al*., 2013). Another study using ENMs based on two climate models (AOGCM and MIROC5) and two climate change scenarios (RCP2.6 and 8.5) predicted by 2090–2100 that the warm-water kelp *L. ochroleuca*, currently limited to south-west England, would remain stable in its current range, but expand through south-west England and Wales under RCP 2.6 and throughout the entire UK where suitable habitat exists (i.e. southern and south-west England, Wales, Northern Ireland and western and northern Scotland, including the Orkney and Shetland Islands) under RCP8.5 (Assis *et al*., 2018). In contrast, *L. hyperborea* and *A. esculenta* would be lost from southern England and Wales under RCP8.5 but persist in these regions under RCP2.6 (Assis *et al*., 2018). Under RCP 8.5, loses of *S. latissima* and *L. digitata* are predicted in south-west England by 2090–2100, but these species remain stable throughout the rest of the UK (Assis *et al*., 2018). The predicted range contraction for *L. digitata* is slightly more conservative than that reported by Raybaud *et al*. (2013) and is likely a result of different methodologies, climatic predictors and climate models used. Assis *et al*. (2018) also suggested that *S. polychides* populations would remain stable in the UK.

Changes in the relative abundance or distribution of different kelp species may, therefore, have knock-on effects for the wider community. While superficially similar, recent research has demonstrated that stipes of the cold-water species dominant, *L. hyperborea* support 12 times as many sessile taxa (flora and fauna) and over 3600 times as much epibiota biomass as the warm water species, *L. ochroleuca* (Teagle and Smale, 2018). Teagle and Smale (2018) also showed that holdfast communities differed between these species, though to a lesser extent than the stipes, supporting previous research which compared *L. ochorleuca* holdfast communities with the colder-water species *L. digitata* (Blight and Thompson, 2008). Collectively these results suggest that climate mediated changes in kelp identity may result in wide-scale ecological change that has implications for higher order consumers such as crustaceans and finfish and therefore fisheries and society.

Maerl beds are made up of living and dead calcareous red algae and support high levels of diversity and are particularly susceptible to changes in ocean carbonate chemistry. Increases in SST/SBT are also likely to impact maerl beds as the development of reproductive conceptacles and growth optimally occur at lower temperatures than those predicted for UK waters into the future (Martin and Hall-Spencer, 2017).

Cold-water coral reefs and gardens

Ocean acidification could threaten scleractinian corals, due to their aragonitic skeletons and gorgonians that secrete magnesium carbonate (Kenchington *et al*., 2012, Büscher *et al*., 2022). However, experiments suggest that scleractinian corals demonstrate high resilience to ocean acidification alone and in combination with ocean warming, due to their capacity to increase pH within their internal calcifying fluid inducing carbonate precipitation (FAO, 2019).

Continued decrease in pH will also increase the dissolution of dead framework (Hennige *et al*., 2015, 2020; Büscher *et al*., 2022; Wolfram *et al*., 2022; Krueger *et al*., 2023), which can form about 70% of the *D. pertusum* coral colonies (Vad *et al*., 2017). Dissolution of dead coral material through the development of coralporosis (Hennige *et al*., 2020) is expected to lead to potential collapse of the reef framework and loss of complexity in these habitats, with potentially large consequences on the associated fauna (Hennige *et al*., 2020; Barnhill *et al*., 2022). Ocean acidification might be advantageous to boring sponges (Duckworth and Peterson, 2013; Wisshak *et al*. 2014), which could accelerate the collapse of reef frameworks but the bioerosion process in the deep sea is currently poorly understood (Büscher *et al*., 2019). Dissolution will become a threat of particular importance for deeper scleractinian coral habitats where the aragonite saturation horizon could shoal above current cold-water coral reefs (Hennige *et al*., 2023). Shallower cold-water coral reefs in UK waters such as the Mingulay reef complex are not expected to be exposed to aragonite undersaturated waters and might therefore constitute a refugia for *D. pertusum* (Findlay *et al*., 2013, 2014).

Caryophyllidae species have also been shown to tolerate decreases in pH (Gori *et al*., 2016, in Last *et al*., 2019). However, these studies do not consider the impact of acidification in combination with reduction of POC flux. If food supply reduces, this could result in a shift in energy allocation away from calcification and growth (FAO, 2019; Sweetman *et al*., 2017). Research on other corals is limited, but gorgonians have been suggested to be more vulnerable than stony corals to ocean acidification (FAO, 2019). Increasing ocean temperature is more likely to impact coral gardens than acidification, with warming reducing calcification of some scleractinians, such as Caryophyllidae (Gori *et al*., 2016). However, warming is more likely to impact corals living close to their upper physiological thermal limit such as in the Mediterranean and Gulf of Mexico (Puerta *et al*., 2016). Knowledge of temperature increases on other coral species is poorly understood. Evidence on impacts of oxygen reductions on coral gardens is limited. However, some research suggests that this can lead to decreased abundance of octocorals, which in turn will impact habitat availability and complexity and reduce associated benthic biodiversity (Sweetman *et al*., 2017).

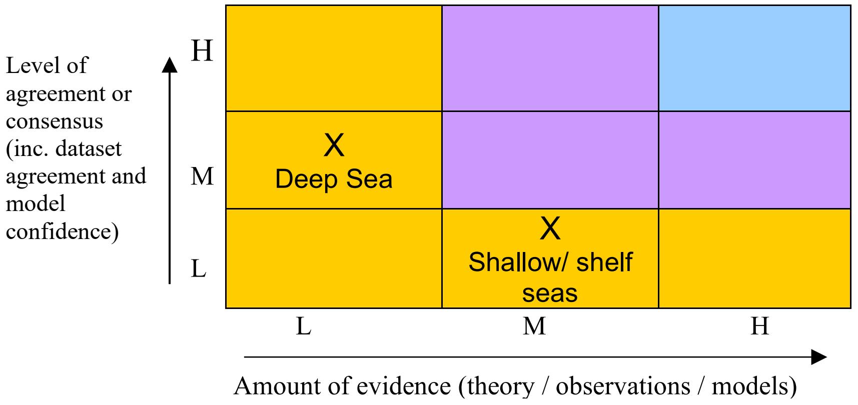
Overall, projections to end of the century conditions have predicted a severe decline in habitat suitability for cold-water corals including *D. pertusum* across the North Atlantic Ocean (Morato *et al*., 2020). *D. pertusum* might see the largest decline in suitable habitat with only 30 to 42% of present-day habitat persisting as climate refugia, including potential loss of octocoral species (Morato *et al*., 2020) and changes in particulate organic fluxes, temperature and aragonite saturation horizon drive predicted shift in habitat suitability (Morato *et al*., 2020; Tong *et al*., 2023).

Deep-sea sponge aggregations

As deep-sea sponge ground distribution is tightly related to water mass properties and circulation, any changes in ocean circulation due to climate change will lead to change in deep-sea sponge distribution (Puerta *et al*., 2020; Roberts *et al*., 2021). Nevertheless, studies considering the long-term temporal variability of water masses over the last 100s to 1000s of years have shown that deep-sea sponge grounds can persist in the face of large past environmental variability (Murillo *et al*., 2016; Beazley *et al*., 2018; Samuelsen *et al*., 2022). The capacity of deep-sea sponge grounds to withstand future climate change is therefore unknown.

CONFIDENCE ASSESSMENT

What is already happening?

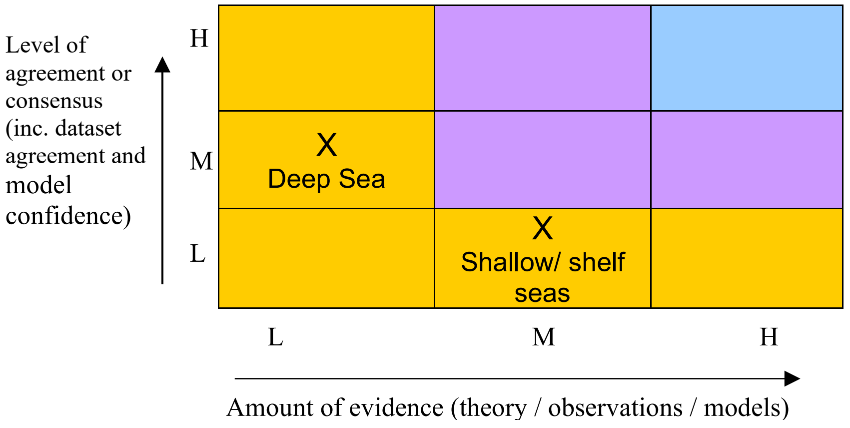


There have been a few studies investigating the impacts of climate change in the UK's shallow and shelf seas since the last relevant MCCIP Report Card in 2020, we would suggest that this is for a limited number of species and either over a very limited spatial scale or a global scale. For example, there is strong evidence that some species of kelp are responding to changes in temperature, but we know little about how this is affecting the large number of species reliant on kelp forests for habitat and food. We are also increasingly confident of the drivers of change in infaunal communities associated with a single long-term monitoring site in the North Sea but have much less knowledge regarding the other regions of the UK. For this reason, we assess that the observational evidence is medium, but the level of consensus remains low.

There is a high level of agreement and medium level of evidence concerning how the environment (food supply, physical oceanography) structures and shapes deep-sea communities and ecosystems. However, there is a medium level of agreement and low amount of evidence concerning how deep-sea habitats are currently being affected by climate change.

There is currently no comparable dataset for the variety of deep-sea habitats that exist within the UK. Even globally, few in-situ observations exist that can confirm the projected consequences of change in deep sea oceanographic conditions to species and productivity redistributions, habitat compression, biodiversity loss and changes in body size (Levin, 2021).

What could happen in the future?



MHWs are predicted to increase in frequency, spatial extent and duration into the future (Frölicher *et al*., 2018). While there is currently no published evidence of the impacts of MHWs in shallow and shelf seas in UK waters, this is likely to change into the future. ENMs are becoming increasingly sophisticated and estimate current species distributions with some confidence, but again these are limited to a small number of taxa. In addition, such models do not take into account interacting stressors or changes in biotic interactions that may occur in response to climate change. We suggest that the evidence from models is still ‘medium’ since the last review, but the level of consensus is still low due to the limited number of taxa investigated and the range of interacting factors that are not included in ENMs.

There is a medium level of agreement on the possible effects of climate change on UK deep-sea habitats. The models used to predict the effects of climate change on deep-sea habitats are in agreement and there is good consensus on the direction of the effects of climate change. However, the models do not provide a consensus on the magnitude of the effect of climate change on deep-sea habitats and our understanding of species resilience is incomplete. The amount of evidence is low because most of the models provide global or ocean basin level predictions, with few studies providing regional predictions, for example the UK deep sea or even the North Atlantic.

To increase the level of confidence in predictions of the future effects of climate change on UK deep-sea habitats, further modelling studies are required at a local scale, for example specifically within UK waters.

KEY CHALLENGES AND EMERGING ISSUES

- There is clear evidence on the impact of marine heat waves on intertidal and shallow sea communities, however the impact is less well known in the shelf and deep-sea environments. Field-based observational research would be improved with better monitoring of a range of ecological response variables across wider geographical scales, with a focus on regions that are poorly studied but likely affected by MHWs. The usefulness of controlled experiments would benefit from more-sophisticated manipulations involving multiple stressors, simulations of MHWs with different properties and a greater diversity and number of experimental organisms.

- Given the complexity and uniqueness of the region, targeted research is needed to understand the future biogeochemical, ecological and societal consequences, or potential opportunities, of MHWs in UK waters (Jacobs *et al*., 2024).

- There are few direct observation monitoring programmes in UK waters, therefore it is difficult to observe what impacts climate change is having on them. Deep-sea habitats in UK waters are generally poorly sampled in time and space except for Station M in the Rockall Trough, Darwin Mounds and the Mingulay reef complex, although both sites lack systematic repeat sampling. More investment is required to fully understand what changes in communities are happening in UK waters.

- Regional, rather than ocean-scale, predictions are required to understand how UK habitats will respond to future climate change. Models must consider impacts of multiple stressors on both benthic and pelagic habitats, for example the interaction between ocean acidification and changes in POC.

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