Marine Life Information Network

Marine Biological Association of the United Kingdom

MARLIN – MARINE LIFE INFORMATION NETWORK

HABITAT (BIOTOPE) SENSITIVITY ASSESSMENTS FOR CLIMATE CHANGE PRESSURES

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HABITAT (BIOTOPE) SENSITIVITY ASSESSMENTS FOR CLIMATE CHANGE PRESSURES

1 Introduction

MarLIN[1] (Marine Life Information Network) was tasked with developing a sensitivity assessment for climate change mediated pressures for marine habitats (biotopes). The work was part of a Defra/JNCC project to improve the evidence–base to support 'climate smart' decision-making in the marine environment, with a focus on MPAs. The sensitivity assessments will support the identification of MPA protected features **most at risk** from the effects of climate change.

Sensitivity assessments against relevant climate change pressures and pressure benchmarks will be undertaken for a range of habitats (as biotopes). The assessments include literature review, evidence summaries and sensitivity ranks. Sensitivity assessment will be performed using the current MarESA (Marine Evidence-based Sensitivity Assessment) methodology[2], and biotopes will include biotopes for two case study MPAs. The resultant sensitivity assessments will form part of the current MarESA sensitivity dataset and available via the MarLIN website.

Sensitivity assessments review the evidence on the likely effects of a pressure (e.g. temperature) on the key features (e.g. a number of specified species) within a habitat (biotope), and their potential rate of recovery once the pressure is removed. The likely effects are **ranked**[3] using defined scales (Tyler-Walters *et al.,* 2018) against **a defined pressure and 'benchmark level' of effect**. The benchmarks are designed to provide a 'standardized' level of effect against which to make an assessment. Where possible benchmarks are quantified in terms of magnitude, extent, duration or frequency. The definition of pressures and benchmarks is the first step toward the assessment of sensitivity.

This project aimed to develop pressure definitions and benchmarks for the following selection of climate change mediated pressures.

- Sea surface temperature and air temperature.
- Ocean acidification.
- Sea-level rise.
- Storms and waves; and possibly
- Freshwater input and salinity.

2 Methodology and consultation

Draft pressures and benchmarks were developed based on a short review of the available literature, primarily informed by the evidence compiled by the International Union for Conservation of Nature (IUCN), the Marine Climate Change Information Partnership (MCCIP), the UK Climate Projections 2018 (UKCP18), the International Panel on Climate Change (IPCC) and others. The review informed our approach to the development of an initial set of draft pressures and benchmarks. These were circulated to a number of national and international experts who were asked to comment on the overall approach to the definition of pressure benchmarks for climate change mediated pressures.

[1] https://www.marlin.ac.uk
[2] https://www.marlin.ac.uk/sensitivity/sensitivity_rationale
[3] Sensitivity assessments are 'ranks' that aim to identify species or habitats that are 'most' sensitive to a given pressure and, hence, prioritize management action.

In particular, experts were asked to comment on the following.

- Does the benchmark reflect the current evidence and predictions?
- Is the choice of benchmark (i.e. the chosen value) valid or defensible based on the levels of uncertainty in the predicted effects of climate change?
- Is our choice of climate change scenario(s) sensible?
- Is there likely to be enough evidence on a broad range of marine habitats to allow sensitivity assessment, i.e. is the benchmark applicable to the evidence base?

We are grateful to representatives of the following organizations who responded to the consultation.

- IUCN (International Union for Conservation of Nature).
- PML (Plymouth Marine Laboratory, UK).
- Cefas (Centre for Fisheries and Aquaculture Science, UK).
- Meteorological Office, UK.
- University of Plymouth, UK
- MBA (Marine Biological Association of the United Kingdom)

The consultees highlighted further up-to-date information resources and were broadly supportive of the overall approach. In particular, the consultees emphasized the following points.

- The importance of capturing the uncertainty in the climate change predictions within the design of the benchmarks, and
- Hence the need to include the upper percentile predictions, especially with respect to temperature rise.
- The importance of distinguishing between the effects of changes in both pH and aragonite concentration due to ocean acidification, depending on the habitats and species concerned.
- And highlighted that sea-levels were rising faster than previously predicted.

The initial draft pressure definitions and benchmarks were amended based on the comments received. In particular, 'extreme scenario' benchmarks were added to the list of benchmarks for both temperature rise (henceforth 'global warming') and 'sea level rise', to capture to the upper range (75-95 percentile) predictions in each case.

3 Approach

Modelling future climate change is fraught with uncertainties; uncertainties in future emissions and mitigation strategies, uncertainties in assessing future changes in key components of climate models such as solar radiation and volcanic activity (Myhre *et al.*, 2013), the counter effects of aerosols (Ramanathan *et al.*, 2001, Rosenfeld *et al.*, 2014) and ocean heat transport (Mahlstein & Knutti, 2011), and uncertainties in climate projection (i.e. choice of climate model (model structural uncertainty) and the choice of model physics (e.g. parameter uncertainty). In order to incorporate some of that uncertainty, different greenhouse gas concentration trajectories have been developed and adopted by the IPCC. These trajectories were developed incorporating aspects such as economic growth, population growth and reliance on fossil fuels, and are used to model atmospheric carbon dioxide concentrations. The Special Report on Emissions Scenarios (SRES) scenarios were used in the IPCC Third and Fourth Assessment Reports (2001 and 2007), with the A1B scenario being representative of a middle emission scenario, and the A1F1 representative of a fossil fuel intensive high emission scenario.

These scenarios were then superseded by the Representative Concentration Pathways (RCPs) that project emissions and concentrations of all greenhouse gases (GHGs) and aerosols and chemically active gases, as well as land use/land cover under different scenarios (van Vuuren *et al.*, 2011). These scenarios were used in the IPCC Fifth Assessment Report (2014), with RCP 4.5 representing a middle emission scenario, and RCP 8.5 representing a fossil fuel intensive high emission scenario. Multiple climate models have then used these scenarios to project changes in climate pressures such as global and ocean warming, ocean acidification and sea-level rise.

When developing pressure benchmarks, we used a **multiple benchmark approach**, whereby we apply sensitivity assessments to the mean projected values for both the middle and high emission scenarios. In the case of global warming and sea-level rise, we also incorporated an 'extreme' scenario. Currently, the trajectory of global emissions are following the RCP 8.5 high emission scenario pathway, due to increased global economic growth (Peters *et al.*, 2012). The 'extreme' scenario was included to capture the predicted upper range (i.e. the 75-95 percentile) of potential global warming and sea-level rise, especially as sea-level rise is increasing faster than previously thought (Laffoley & Baxter, 2016; Lowe *et al.,* 2018; Palmer *et al.,* 2018; IPCC, 2019; Laffoley, Buckley *pers comm*. 2019).

Climate change impacts may vary regionally so we have preferentially used predictions that are specific to the UK/ North Sea/ north-western European shelf seas where values are available, in order to incorporate regional variation into the benchmarks for sensitivity assessments. Where possible, we used projections using the latest climate trajectory scenarios (RCPs) if available. Otherwise SRES scenarios were used.

The predicted effects of pressures are often expressed as a range of values within defined levels of probability. However, a range of potential values would result in a range of sensitivity assessments and our preference is for a single value for each of the middle or high emissions scenarios or extreme scenario. We hoped to capture the potential variation in sensitivity by using a benchmark for each scenario. Therefore, we used the median or mean value for each scenario as the 'most likely' predicted outcome, in order to simplify application of evidence to sensitivity assessment. Where appropriate, median/mean values were rounded to the nearest degree/unit, as it may be difficult the compare fractions of a degree/ unit to the reported evidence on the effects of pressures. Similarly, we recognized that end dates differed between studies (e.g. 2070-2099, 2085-2095) when modelling projected climate impacts but, as most of these models aim to compile a picture of potential impacts by the end of this century (2081-2100), we refer to pressure 'benchmarks' as such.

4 Global warming (sea and air temperatures)

The IPCC projected increase in North Atlantic sea surface temperature (SST) is lower than the regional and more recent SSTs projected by Tinker *et al.* (2016) or Alexander *et al.* (2018) for UK seas (Table 1). This is primarily due to the large expanse of open ocean within the North Atlantic, which is predicted to experience lower rates of temperature increase than shelf seas (Holt *et al.*, 2010). The most up-to-date temperature projections for the UK SSTs predict a temperature increase of 2.9°C for the middle emission (A1B) scenario around the north-western European shelf seas (Tinker *et al.*, 2016), and an increase of 4.1°C using the high emission scenario (RCP 8.5) (Alexander *et al.,* 2018). In the case of an extreme scenario, whereby temperatures rise within the upper likely range of the high emission scenario, sea temperatures around the UK are expected to rise by 4.7°C (75th percentile; Alexander *et al.*, 2018). SST warming will vary regionally around the UK, with the shelf edge and open ocean experiencing the lowest temperature increase (Lowe *et al.*, 2009). Projected differences between mean SST increases for the different UK shelf seas are thought to be low (0.5°C difference between the northern and southern North Sea), and values overlap in likely ranges (Tinker *et al.*, 2016, Table 2). Similarly, whilst increases in projected near-bottom temperatures for the UK shelf seas are slightly lower than SST, likely range of values (±S.E.) overlap (Table 2), and hence temperature changes for both sea surface temperatures and bottom waters on the UK continental shelf will be assessed against the same value.

Table 1. End of century SST projected increases in relationship to different emission scenarios. Key values used to determine the suggested benchmarks are highlighted in bold. (**= no data, the scenario was not addressed within the cited report)

IPCC AR5 2013		Tinker *et al.,* 2016			Alexander *et al.,* 2018		
2099 North Atlantic projection		2069 – 2089 UK shelf seas			1985 – 2095 increase North Sea		
Scenario	Mean	Scenario	Mean	±2σ	Scenario	Median	IQ range
RCP 2.6	0.54	**	**	**	**	**	**
RCP 4.5	1.54	**A1B**	**2.9**	0.82	**	**	**
RCP 6.0	1.95	**	**	**	**	**	**
RCP 8.5	3.02	**	**	**	**RCP8.5**	**4.1**	3.1 **-4.7**

Table 2. End of century projected change (2069–2098 relative to 1960–1989) in annual mean sea-surface temperature (SST), and near-bottom temperature (NBT) averaged over shelf regions.

	Shelf	Southern North Sea	Central North Sea	Northern North Sea	English Channel	Irish Sea	Celtic Sea
Ann dSST (°C)	2.90 (±0.82)	3.26 (±0.72)	3.15 (±0.75)	2.75 (±0.75)	3.13 (±0.82)	3.08 (±0.85)	3.01 (±1.04)
Ann dNBT (°C)	2.71 (±0.75)	3.22 (±0.71)	2.92 (±0.63)	2.53 (±0.63)	3.04 (±0.79)	3.00 (±0.82)	2.54 (±0.88)

The edge of the shelf and off-shelf, deep water habitats (such as the Canyons MCZ) are projected to see minimal temperature change, as deep Atlantic waters are not expected to see the same scale of rise as sea surface temperature within in the given timescale (Figure 1).

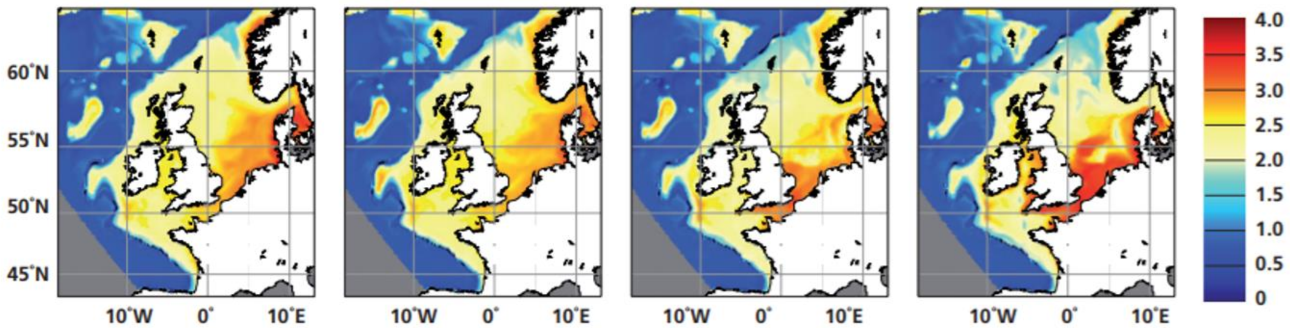

Figure 1. End of the century projected seasonal mean near-bottom temperature (NBT) change for end of the century (2070-2098 relative to 2061–1990) (UKCP18 Lowe *et al.*, 2009).

Reid (2016) noted that the systematic measurement of the sea below 2,000 m is limited geographically and to the last three decades so that estimates of warming are less precise. Nevertheless, models suggest that deep and abyssal basins have absorbed substantial amount of heat and indicate that temperature rises of 0.5-1.5°C (depending on the emission scenario) could extend to 1,000 m by the end of the century, depending on the emission scenario. Modelling of the deep-sea ecosystem (FAO (Fisheries and Aquaculture Organisation), 2019) also suggest that some of the deep-sea basins could see up to 2°C rise in temperature between 200 and 2,500 m, by 2081-2100 using the RCP8.5 scenario but that the Atlantic and Arctic Oceans would be lower, with a mean rise of ca 1°C (0.98 and 0.93°C respectively).

The projected mean surface (air) temperature rises towards the end of this century follow a similar pattern to sea surface temperatures. Projections of global surface temperature increases do not differ between 2013 -2019 projections (IPCC, 2013, 2019, Table 3). UKCP18 predict mean UK surface temperature rises of 2.7°C and 3.9°C under the middle (A1B[4]) and high (RCP8.5) emission scenarios respectively (Table 3, Figure 2).

Table 3. Future projections of increases in surface air temperature in relationship to different emission scenarios. Key values used to determine suggested benchmarks are highlighted in bold.

IPCC AR5 2013			IPCC SROCC 2019			UKCP18		
2081 - 2100 Global average relative to 1986-2005			2081 - 2100 Global average relative to 1986-2005			2080 – 2099 UK average relative to 1981 - 2000		
Scenario	Mean	5-95%	Scenario	Mean	5-95%	Scenario	Median	10-90%
RCP 2.6	1.0	0.3 – 1.7	RCP 2.6	1.0	0.3–1.7	RCP 2.6	1.4	1.5 – 2.3
RCP 4.5	1.8	1.1 – 2.6	RCP 4.5	1.8	1.0-2.6	**A1B**	**2.7**	2.3 – 4.1
RCP 6.0	2.2	1.4 – 3.1	RCP 6.0	2.7	1.3-3.2	**	**	**
RCP 8.5	3.7	2.6 – 4.8	RCP 8.5	3.7	2.5-5.4	**RCP 8.5**	**3.9**	2.3 – **5.7**

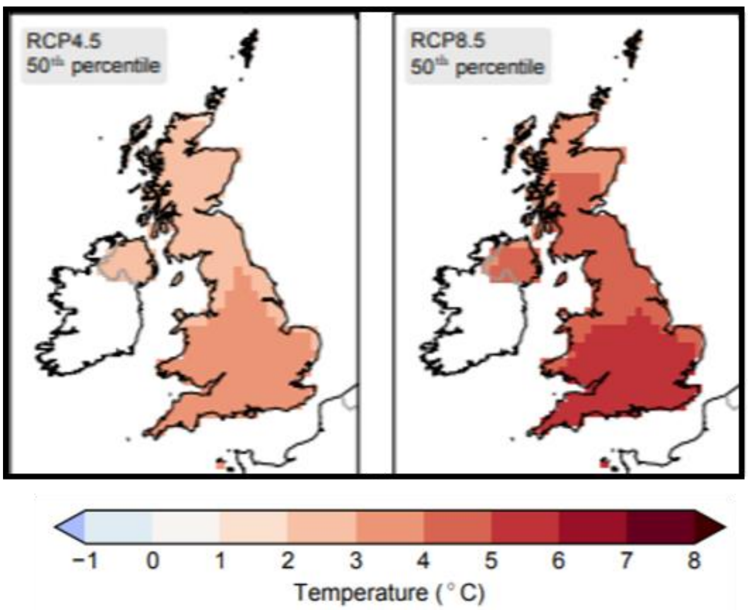

Figure 2. End of the century projected summer temperature anomaly (2080–2099 relative to 1981–2000) (UKCP18 Lowe *et al.*, 2018).

Surface (air) temperatures rises are projected to be more severe in summer than in winter, with more heatwaves occurring under both middle and high emission scenarios (IPCC, 2019) and more severe in the south than the north (Lowe *et al.*, 2018). In the case of an extreme scenario,

[4] Please note A1B was superseded by the RCP4.5 scenario, however, we have used A1B where no data for RCP4.5 is presented.

whereby temperatures rise within the upper likely range of the high emission scenario, air temperatures around the UK are expected to rise by 5.7°C (90th percentile: UPCP18).

As mean surface temperature increases are similar to SST increases, we have combined surface temperature benchmarks and sea surface temperature benchmarks (except in the 'extreme' scenario), although we recognise that surface (air) temperature rise is only relevant for intertidal species and habitats. Intertidal species that only occur in Scotland will be assessed against a 1°C lower temperature rise, to take regional variation into account (Figure 2).

Hence, the following benchmarks were suggested, using rounded values.

Middle emission scenario (A1B) (by the end of this century 2081-2100) benchmark of:

- A 3°C rise in SST, NBT (coastal to the shelf seas) and surface air temperature (in eulittoral and supralittoral habitats);
- A 1°C rise in deep-sea habitats (>200 m) off the continental shelf; and
- A 2°C rise in surface air temperature in intertidal habitats exclusive to Scotland.

High emission scenario (RCP8.5) (by the end of this century 2081-2100) benchmark of:

- A 4°C rise in SST, NBT (coastal to the shelf seas) and surface air temperature (in eulittoral and supralittoral habitats);
- A 1°C rise in deep-sea habitats (>200 m) off the continental shelf, and
- A 3°C rise in surface air temperature in intertidal habitats exclusive to Scotland.

Extreme scenario (RCP8.5 upper range) (by the end of this century 2081-2100) benchmark of:

- A 5°C rise in SST and NBT (coastal to the shelf seas);
- A 6°C rise in surface air temperature (in eulittoral and supralittoral habitats);
- A 1°C rise in deep-sea habitats (>200 m) off the continental shelf, and
- A 5°C rise in surface air temperature in intertidal habitats exclusive to Scotland.

5 Marine heatwaves

A marine heatwave can be defined as a period when SSTs exceeds its local 99th percentile, as defined by daily observations of satellite data (Frölicher *et al.*, 2018), and occurs when air temperatures exceed the seasonal average (Garrabou *et al.*, 2009). Marine heatwaves have already doubled in frequency since the 1860 - 1880 baseline, and it is very likely that 84-90% of marine heatwaves occurring 2005-2016 are attributable to anthropogenic temperature rises (Frölicher *et al.*, 2018). Marine heatwaves are expected to increase in frequency, duration, extent and intensity, with climate models predicting that the frequency of marine heatwaves will increase 50 fold for RCP 8.5 and 20 fold for RCP 2.6 by 2081-2100 relative to 1850-1900 (IPCC, 2019).

Marine heatwaves can be caused by a range of factors, such as:

- air-sea heat flux when surface temperature reaches anomalously high temperatures such as the heatwave experienced in the Mediterranean in the summer of 2003 (Smale *et al.*, 2019);
- a decrease in heat loss and a reduction in cold advection which caused a persistent (2013-2016) warm heat anomaly 'the Blob' in the NE Pacific (Bond *et al.*, 2015), and
- El Nińo events in the tropical pacific (Holbrook *et al.*, 2019).

The Mediterranean heatwave of 2003 saw air temperatures soar to 3-6°C above mean seasonal temperatures, lasting from early June until mid-August. It led to a marine heatwave where mean and maximum SSTs were between 1 and 3°C higher than average, which saw widespread mortality on rocky reefs (Garrabou *et al.*, 2009).

Heatwaves caused by increased air-sea heat flux due to significantly warmer summer temperatures are the most likely heatwaves that the UK will face in the future (D. Smale, *pers. comms.*). These heatwaves generally only impact shallow waters habitats (≤ 50 m). For example the Mediterranean heatwave of 1999 showed an increase in seawater temperatures down to approximately 50 m depth (Cerrano *et al.*, 2000), whilst the Mediterranean heatwave of 2003, led to biological effects down to a depth of 40 m (Garrabou *et al.*, 2009). As there is currently not enough information to project increases in heatwaves from other sources, such as changes in ocean currents (D. Smale, *pers. comm.*), this pressure will focus on heatwaves caused by air-sea flux.

Frölicher *et al.* (2018) used satellite observations and Earth systems models to show that marine heatwaves have already become longer lasting and more frequent, and that this trend will accelerate into the future (Figure 3). By the end of this century, almost 100% of marine heatwaves will be attributable to climate change (Fig. 3f). Global modeling shows that the likelihood of UK waters experiencing a heatwave will be approximately 15 times more likely under global warming of 3.5°C by the end of this century (high emission scenario; Figure 4), whilst under global warming of 2°C, the likelihood of UK waters experiencing a heatwave will be approximately 10 times more likely (middle emission scenario; Figure 4). Towards the end of last century (1981-2000) the UK experienced hot spells on land approximately every four years, yet under the high emission scenario (RCP8.5) the UKCP project that number is expected to increase to four times a year by 2070 (Madge, 2019). As marine heatwaves occur through increased air-sea heat flux, this, combined with global projections (Frölicher *et al.*, 2018) suggest that marine heatwaves will occur much more frequently by the end of this century under both mid- and high-emission scenarios.

Therefore, the following benchmarks were suggested, based on the projections presented in Figure 3 and 4 (Frölicher *et al.*, 2018), and UKCP18 projections. Under a high emission scenario marine heatwaves could occur every two years, lasting a duration of 120 days (see Fig. 3c), and with a maximum intensity of 3.5°C (Fig. 3d).

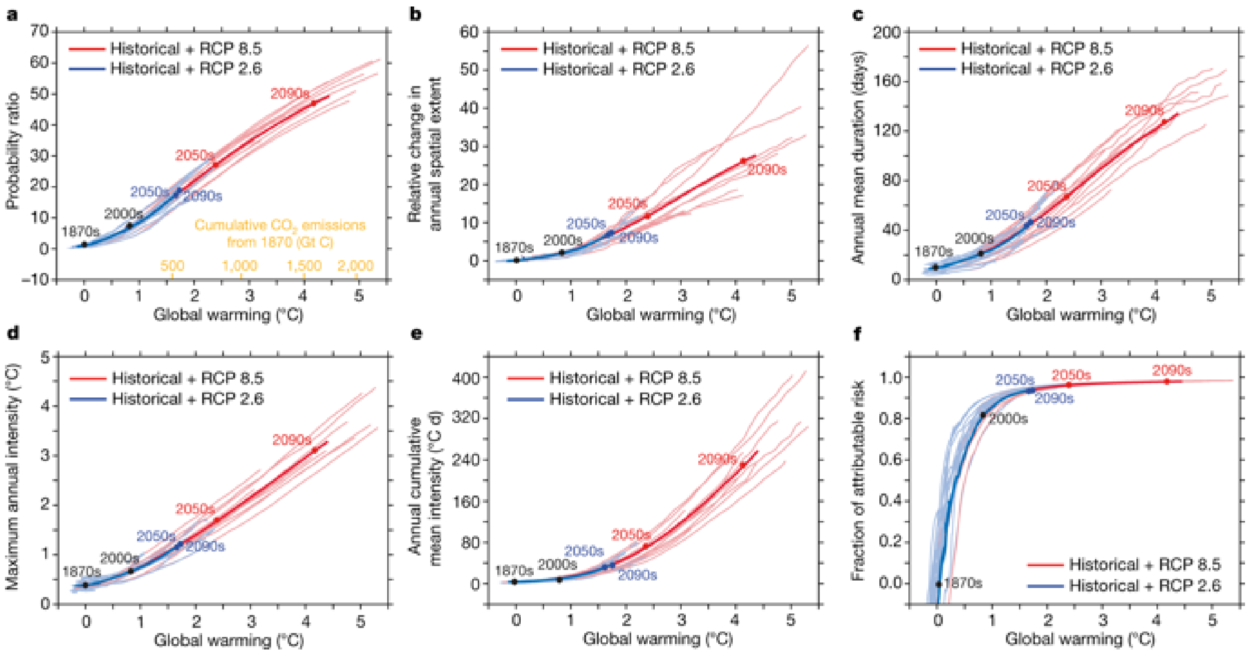

Figure 3. Future projections of the global aggregated annual mean probability ratio (a), relative change in spatial extent (b), duration (c), maximum intensity (d), cumulative mean intensity (e) and fraction of attributable risk (f) of MHWs exceeding the 99th preindustrial percentile (from Frölicher *et al.*, 2018).

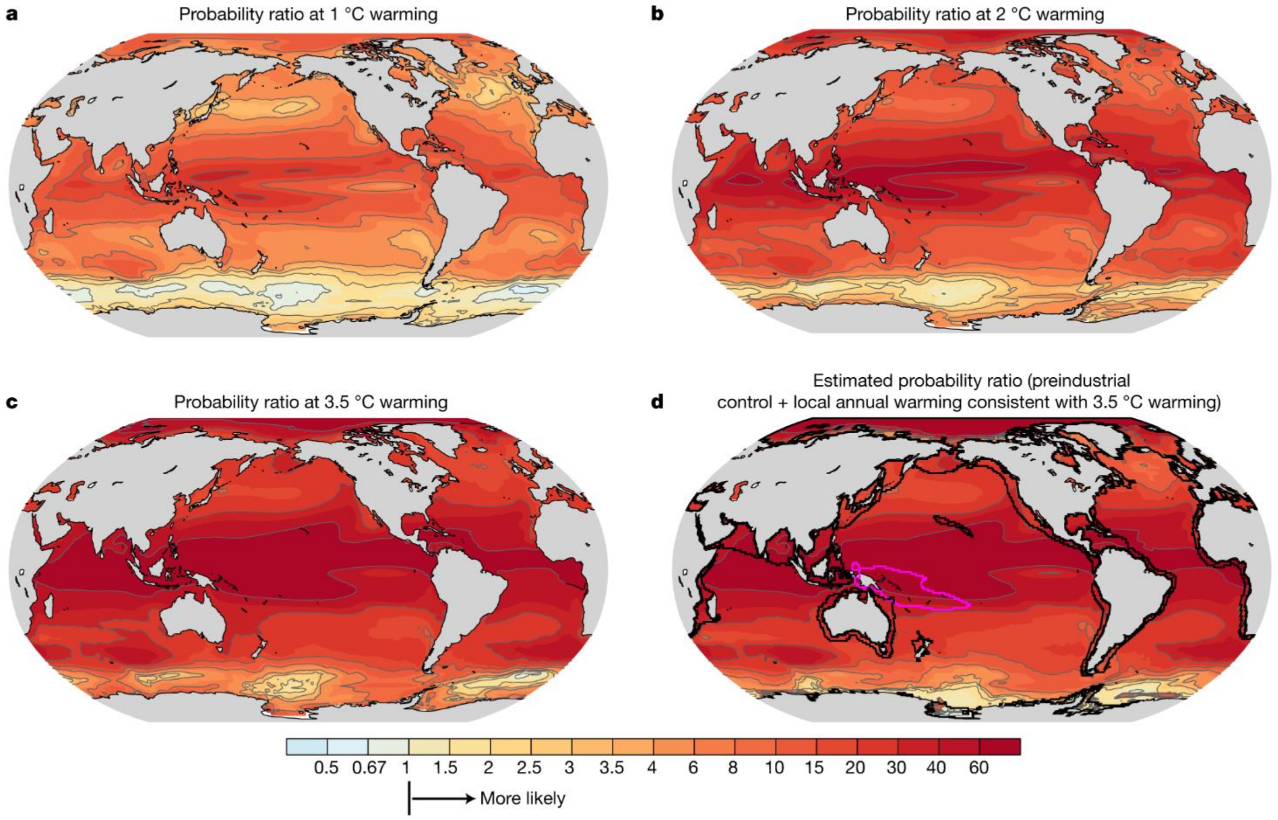

Figure 4. Changes in the probability of MHW days exceeding the preindustrial 99th percentile for a global warming level of 1°C (a), 2°C (b) and 3.5°C (c). To show that the occurrence of MHWs is mainly driven by a simple shift of the whole temperature distribution, in d we have added the local annual SST change that is consistent with a 3.5°C global warming to the preindustrial SST distribution (from Frölicher *et al.*, 2018).

Under the middle emission scenario marine heatwaves could occur every three years, lasting a duration of 80 days (see Fig. 3c), and with a maximum intensity of 2°C (Fig. 3d). The resultant pressure benchmarks are expressed as follows.

- **Middle emission scenario benchmark:** a marine heatwave occurring every three years, with a mean duration of 80 days, with a maximum intensity of 2°C.
- **High emission scenario benchmark:** a marine heatwave occurring every two years, with a mean duration of 120 days, and a maximum intensity of 3.5°C.

6 Ocean acidification

The pH of surface waters are highly variable over time (Figure 5), which reflects seasonal cycles in photosynthesis, respiration and water mixing (Ostle *et al.*, 2016). Increasing levels of CO_2 in the atmosphere have led to the average pH of sea surface waters dropping from 8.25 in the 1700s to 8.14 in the 1990s, leading to a 25% increase in H^+ ions (Jacobson, 2005). Marine calcifiers may be particularly at risk, especially as waters suffer from seasonal aragonite undersaturation, leading to dissolution of calcium carbonate. Aragonite saturation state is influenced by dissolved inorganic carbon (DIC) concentration, pressure and temperature so that deep waters, which have high levels of DIC, high pressure and low temperatures, will be the first habitats to face strong, seasonal undersaturation (C. Ostle *pers. comm.*).

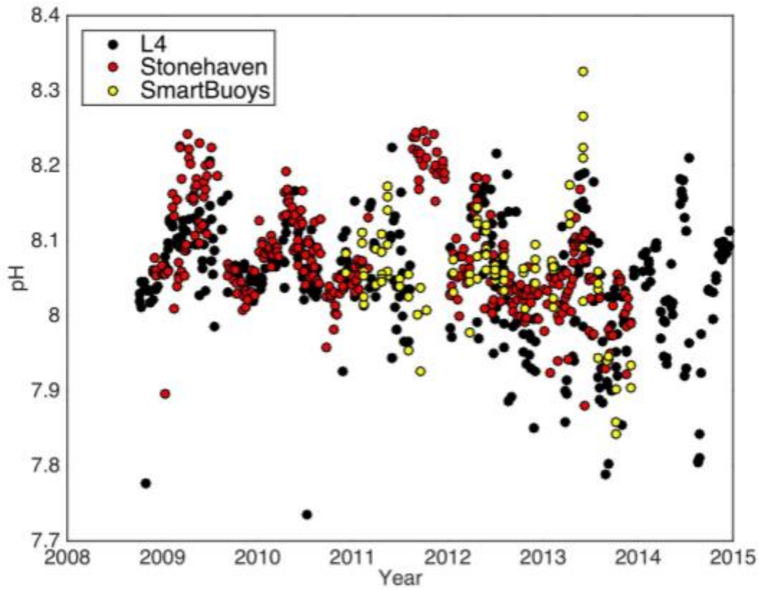

Figure 5. UK pH data 2008 –2015 for time series at L4 (off Plymouth), Stonehaven (near Aberdeen) and for Smart Buoys in the North Sea and Irish Sea (Ostle *et al.*, 2016).

Global ocean pH is expected to decrease by a further 0.07 -0.33 units by the end of this century, dependent on emission scenario (Bopp *et al.*, 2013; Table 4). Regional modelling seems to show slightly elevated pH decreases, with end of century predictions using the RCP8.5 emissions scenario leading to a projected decrease of 0.36 pH units for the North Sea and 0.33 pH units for the Celtic Seas (Ostle *et al.*, 2016).

Seasonal aragonite saturation is likely to occur under the high emission scenario, with surface aragonite becoming undersaturated in the winter months (Figure 6). On the other hand, the bottom waters of the North Sea will face undersaturation during summer months, due to seasonal stratification (Artioli *et al.*, 2014; Figure 6). Aragonite undersaturation is most likely to occur in surface waters (0-30 m), where seasonal stratification occurs, and deep waters.

Table 4. Future projections of decreases in pH in relationship to different emission scenarios. Key values used to determine the suggested benchmarks are highlighted in bold.

Bopp *et al.* 2013 (IPCC AR5)			Artioli *et al.* 2014			Ostle *et al.* 2016		
2090-2099 global average decrease			2080-2099 UK shelf seas average relative to 1981 - 2000			2080-2099 UK shelf seas average relative to 1990 - 2009		
Scenario	Mean	± S.E.	Scenario	Mean	± S.E.	Scenario	Mean	± S.E.
RCP 2.6	0.07	±0.001	**	**	**	**	**	**
RCP 4.5	**0.15**	±0.001	A1B	0.27	**	**	**	**
RCP 6.0	0.22	±0.002	**	**	**	**	**	**
RCP 8.5	**0.33**	± 0.003	**	**	**	**RCP 8.5** **North Sea** **Celtic Sea**	 **0.36** **0.33**	 0.034 0.019

In deep waters the aragonite saturation horizon (ASH) is defined as the depth in the oceans at which aragonite saturation equals 1. Below this depth, the aragonite saturation state (Ω_{Ar}) will fall below 1 and dissolution of calcified structures that are not protected by living tissue (e.g. coral reef and fragments) may occur. Currently, the depth of the ASH in the North Atlantic is approximately 2000 m (Jiang *et al.*, 2015) but this depth is already 80-150 m shallower than the past two centuries (Chung *et al.*, 2003, Feely *et al.*, 2004). By the end of this century, in the NE Atlantic, the ASH is expected to reach depths of up to 400 m under the high emission scenario (RCP 8.5) and 800 m for the middle emission scenario (RCP 4.5) (Zheng & Long, 2014). Aragonite undersaturation is already occurring in polar seas (Wynn *et al.*, 2016; Figure 7). Future projections of aragonite saturation for the middle emission scenario are unknown.

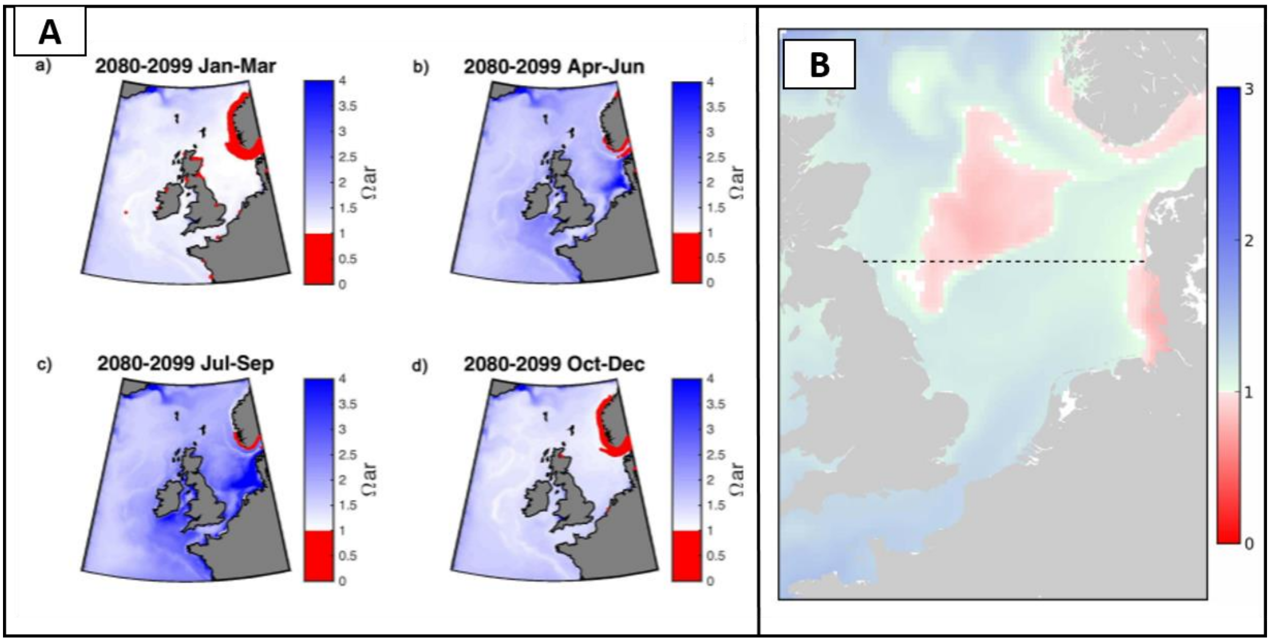

Figure 6. End of century projected minimum aragonite saturation state for A) surface waters under the IPCC RCP 8.5 scenario (from Ostle *et al.*, 2016) and B) bottom waters in the North Sea under the A1B scenario (from Artioli *et al.*, 2014). Red areas highlight undersaturation.

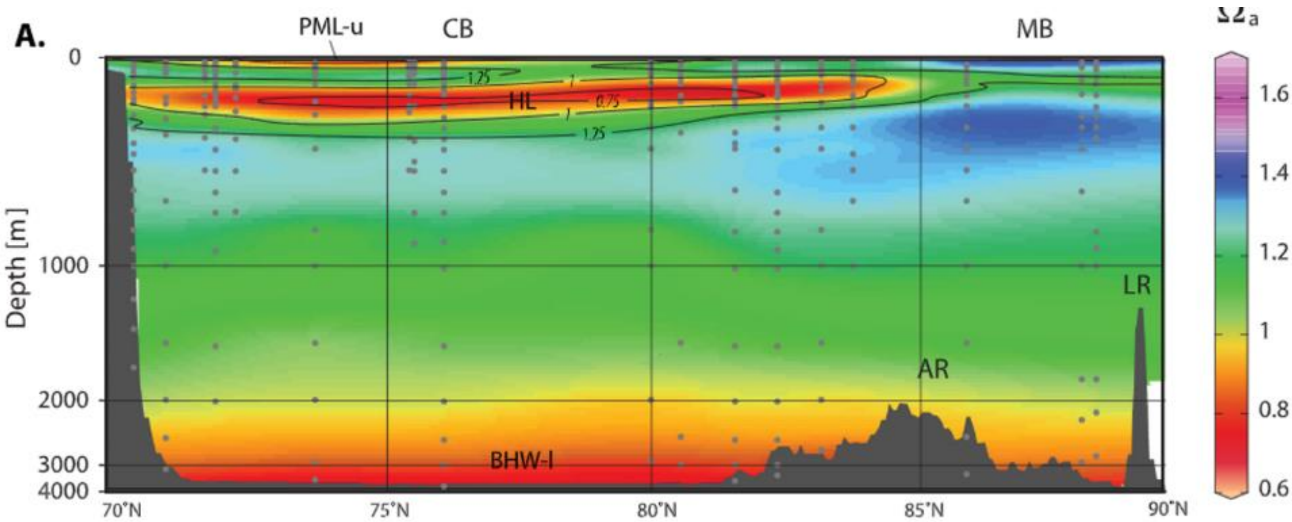

Figure 7. Cross-section of aragonite saturation state of the polar Canada and Makarov basins, showing aragonite undersaturation in the upper polar mixed layer (0-30 m), the halocline layer, and deep (>2,000 m) waters (Wynn *et al.*, 2016).

Therefore, the following pressure benchmarks were suggested using rounded global average projections.

- **Middle emission scenario benchmark:** a further decrease in pH of 0.15 (annual mean) and corresponding 35% increase in H+ ions with no coastal aragonite undersaturation and the aragonite saturation horizon in the NE Atlantic, off the continental shelf, at a depth of 800 m (see description above) by the end of this century (2081-2100).

- **High emission scenario benchmark:** a further decrease in pH of 0.35 (annual mean) and corresponding 120% increase in H+ ions, seasonal aragonite saturation of 20% of UK coastal waters and North Sea bottom waters, and the aragonite saturation horizon in the NE Atlantic, off the continental shelf, occurring at a depth of 400 m (see description above) by the end of this century (2081-2100).

7 Sea-level rise

Sea-level rise is occurring through a combination of thermal expansion and ice melt. Sea-levels have risen 1-3 mm/yr. in the last century (Cazenave & Nerem, 2004, Church *et al.*, 2004, Church & White, 2006). Sea-level rise will vary between the north and south around mainland UK, due to vertical land movement. The Scottish mainland will see reduced sea-level rise compared to the rest of the UK, although the Scottish islands will not (Figure 8). The most recent projections provided by the UKCP18 suggest an increase of 23 –107 cm around the UK depending on location (Table 5). UKCP09 sea-level rise values were lower than UKCP18 levels, as the updated sources included ice dynamics in their measurements; something that was omitted from the UKCP09 projections (Lowe *et al.*, 2018).

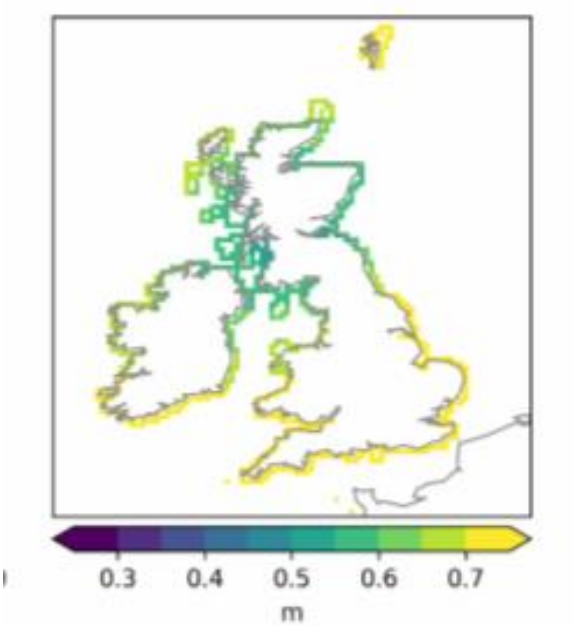

Figure 8. Spatial pattern of change at 2100 associated with mean estimate of RCP 8.5. From Lowe *et al*. (2018).

Table 5. Projected increases in sea-levels (cm). Key values used to determine the suggested benchmarks are highlighted in bold.

IPCC AR5			UKCP09			UKCP18		
2081 - 2100 Global average			2090 – 2099 UK average			2080 – 2099 UK average		
Scenario	Mean	5-95th percentile	Scenario	Median	5-95th percentile	Scenario	Median	5-95th percentile
RCP 2.6	40	26 – 55	B1	30	12 - 48	RCP 2.6	39	23-64
RCP 4.5	47	32-63	A1B	37	13 – 61	**RCP 4.5**	**49**	31-77
RCP 6.0	48	33-63	**	**	**	**	**	**
RCP 8.5	63	45 – 82	A1F1	46	15 – 76	**RCP 8.5**	**70**	**47-107**

Therefore, we suggested using the UKCP18 mean (rounded) values of sea-level rise for the mid and high emission scenario as benchmarks, as these were both the most recent, and regional to the UK. An additional 'extreme' scenario was suggested based on the 95 percentile, in response to the observed acceleration in ice melting and sea-level rise noted in the IPCC SROCC report (IPCC, 2019) and suggested by P. Buckley and D. Laffoley (pers. comm., 2019).

- **Middle emission scenario benchmark:** a 50 cm rise in average UK sea-level rise by the end of this century (2081-2100).
- **High emission scenario benchmark:** a 70 cm rise in average UK by the end of this century (2018-2100).
- **Extreme scenario benchmark:** a 107 cm rise in average UK by the end of this century (2018-2100).

8 Storms and waves

As yet, there is no consensus on the future storm and wave climate (Lowe *et al.*, 2018). Several global and regional wave models have explored the potential changes in mean and significant wave height in response to the RCP8.5 worst case scenario, and suggest a possible 10% to 20% decrease in the future, whilst projections of storm surge in the future were either positive or negative, dependent on the model used (Lowe *et al.*, 2018). The UKCP18 suggested that there was the potential for changes in the severity of storm surge events but that the model suggested a small contribution to sea-level rise from storm surges and was not able to predict if storm surges were likely to become more or less severe or remain the same (Palmer *et al.*, 2018).

Therefore, we concluded that it was not possible to suggest a benchmark value for storms and waves, at present.

9 Freshwater input and salinity

Recent modelling for the north-west European shelf predicts a salinity decrease of 0.41 psu ±0.06 psu by the end of this century (Tinker *et al.*, 2016). Whilst salinity is fundamental in modifying aquatic assemblage structure, a decrease of this magnitude is not thought to be enough to invoke a biotic response. Therefore, we suggest that salinity is not included as a separate 'climate change pressure' and suggest that the current 'salinity change' pressure benchmark used within the MarESA approach (Tyler-Walters *et al.,* 2018) will address the potential changes in salinity due to localised runoff that may occur through increased winter precipitation (Lowe *et al.*, 2018).

10 Application

In application, the pressure 'benchmarks' suggested above will provide 'scenarios' against which to assess and 'rank' sensitivity.

10.1 Resistance (tolerance) assessment

The suggested 'benchmarks' represent a predicted level of change (in temperature, sea-level or ocean acidification) by the end of this century. Therefore, a resistance assessment based on the suggested 'benchmark' would represent the likely effect of that magnitude of change rather than the gradual change between the present day and the end of the century. However, where evidence allows we will address information on the effects of gradual change. The exception is the marine heatwaves pressure benchmark that represents the effects of recent marine heatwaves and includes predicted levels of intensity and duration. However, marine heatwaves have already been documented in the marine environment and are likely to continue in coming years or decades.

The following evidence sources were anticipated, based on the literature review to date:

- Modelled predicted changes in peer reviewed journals;
- Laboratory studies investigating the impact of climate change pressures on key species in peer reviewed journals;
- Evidence of the effect of similar events (e.g. marine heatwaves or gradients of temperature or pCO_2 from seeps) on key species/ groups of species;
- Predictions based on proxies such as natural temperature ranges and habitat preferences, and
- Evidence of range shifts in distribution due to temperature or other factors.

We assume that 'sea-level rise' is 'not relevant' for deep-sea habitats (>200 m) and most subtidal habitats except sublittoral fringe habitats but is relevant for eulittoral and supralittoral habitats. Surface (air) temperature will only be relevant to eulittoral, supralittoral, and terrestrial habitats and will not be assessed for sublittoral fringe or sublittoral and deep-sea habitats.

10.2 Resilience (recovery) assessment

In the MarESA approach, resilience (recovery) assumes that the pressure in question stops or is mitigated and the species or habitat experiences the same or similar conditions to those experienced prior to the pressure, after which point recovery can occur. The exceptions are the 'permanent pressures' of 'physical (habitat) loss' and 'physical modification' of the seabed or sediment. In those cases, resilience/recovery is assessed as 'None/Very low'.

We suggest that 'climate change pressures' are, by definition, 'ongoing' (rather than 'permanent') and liable to steadily increase in the future (or hopefully level out) but are not likely to be reversed in any manageable timescale. Therefore, resilience assessment could default to 'None/Very low'. However, there may be caveats or exceptions, as outlined in the following scenarios.

- Opportunistic species with short lifespans and rapid recruitment, may be able to adapt to climate induced changes between the present day and the end of the century and beyond. We include any evidence to that effect and assess recovery accordingly based on the evidence found.
- Potential adaptation by longer-lived species (e.g. *Zostera*) between the present day and the end of the century and beyond. We include any evidence to that effect and assess recovery accordingly based on the evidence found.
- Range shifts , i.e. some species are moving poleward in response to increases in temperature; e.g.:
    - mobile species where individuals and populations may follow prey or suitable habitat parameters (e.g. temperature range) in which case the species population may not be sensitive as it is unlikely to be significantly impacted and can recover by changing its range, depending on its mobility and life history (e.g. fish, sharks etc.);
    - similarly sedentary species that demonstrate range shifts over decades (e.g. gastropods),
    - however, at the habitat level species may either be lost from a habitat in the site of interest, or replaced by another so that the biotope would be lost or replaced within a site, and ranked as highly sensitive as no recovery is likely.

Nevertheless, in most cases we suggest that resilience (recovery) will be 'None/Very low' in most scenarios and sensitivity is likely to be ranked as at least 'Medium' for any species or habitats impacted by climate change pressures.

11 Summary of pressures and benchmarks

The proposed pressures and benchmarks are summarized below for consistency with the existing MarESA list of pressures and benchmarks (Tyler-Walters *et al.,* 2018) and for dissemination via the MarLIN website.

Pressure theme	**Climate change**
Pressure	**Proposed benchmark(s)**
Global warming (sea and air temperature)	**Middle emission scenario (A1B) (by the end of this century 2081-2100) benchmark of:** • A 3°C rise in SST, NBT (coastal to the shelf seas) and surface air temperature (in eulittoral and supralittoral habitats); • A 1°C rise in deep-sea habitats (>200 m) off the continental shelf. • A 2°C rise in surface air temperature in intertidal habitats exclusive to Scotland. **High emission scenario (RCP8.5) (by the end of this century 2081-2100) benchmark of:** • A 4°C rise in SST, NBT (coastal to the shelf seas) and surface air temperature (in eulittoral and supralittoral habitats); • A 1°C rise in deep-sea habitats (>200 m) off the continental shelf, and • A 3°C rise in surface air temperature in intertidal habitats exclusive to Scotland. **Extreme scenario (RCP8.5 upper range) (by the end of this century 2081-2100) benchmark of:** • A 5°C rise in SST and NBT (coastal to the shelf seas); • A 6°C rise in surface air temperature (in eulittoral and supralittoral habitats); • A 1°C rise in deep-sea habitats (>200 m) off the continental shelf, and • A 5°C rise in surface air temperature in intertidal habitats exclusive to Scotland.
	Pressure description
	Global warming results from the retention of thermal energy within the atmosphere and hence the ocean by 'greenhouse' gases, such as CO_2 and CH_4 (amongst others). Since the industrial revolution (in 1800s) the average temperature of the globe has risen by 1°C and the CO_2 concentration in the atmosphere is currently the highest it has been in the last 800,000 years (at over 400 ppm) (Palmer *et al.,* 2018; IPCC, 2019). Since the 1970s, the ocean has absorbed ca 93% of the extra heat (Laffoley & Baxter, 2016). As a result, models predict varying increases in average air and sea surface temperature, depending on the greenhouse gas emission scenario used, well beyond the end of this century (Palmer *et al.*, 2018; IPCC, 2019). Air temperature is included for marine species/habitats in the eulittoral and supralittoral that will be exposed to air when emersed.
Pressure	**Proposed benchmark(s)**
Marine heatwaves	**Middle emission scenario benchmark:** a marine heatwave occurring every three years, with a mean duration of 80 days, with a maximum intensity of 2°C. **High emission scenario benchmark:** a marine heatwave occurring every two years, with a mean duration of 120 days, and a maximum intensity of 3.5°C.

	Pressure description
	A marine heatwave can be defined as a period when SSTs exceeds its local 99th percentile, based on daily observations of satellite data (Frölicher *et al.*, 2018), and occurs when air temperatures exceed the seasonal average (Garrabou *et al.*, 2009). Marine heatwaves have already doubled in frequency since the 1860 - 1880 baseline, and it is very likely that 84-90% of marine heatwaves occurring 2005-2016 are attributable to anthropogenic temperature rises (Frölicher *et al.*, 2018). Marine heatwaves are expected to increase in frequency, duration, extent and intensity, with climate models predicting that the frequency of marine heatwaves will increase 50 fold for RCP 8.5 and 20 fold for RCP 2.6 by 2081-2100 relative to 1850-1900 (IPCC, 2019). Marine heatwaves can be caused by a range of factors, such as: • air-sea heat flux when surface temperature reaches anomalously high temperatures such as the heatwave experienced in the Mediterranean in the summer of 2003 (Smale *et al.*, 2019), • a decrease in heat loss and a reduction in cold advection which caused a persistent (2013-2016) warm heat anomaly 'the Blob' in the NE Pacific (Bond *et al.*, 2015), and • El Nińo events in the tropical pacific (Holbrook *et al.*, 2019). For example, the Mediterranean heatwave of 2003 saw air temperatures soar to 3-6^{0}C above mean seasonal temperatures, lasting from early June until mid-August, and led to occurrence of a marine heatwave where mean and maximum SSTs were between 1 and 3^{0}C higher than average which saw widespread mortality on rocky reefs (Garrabou *et al.*, 2009). Heatwaves caused by increased air-sea heat flux due to significantly warmer summer temperatures are the most likely heatwaves that the UK will face in the future (D. Smale, *pers. comms.*). These heatwaves generally only impact shallow waters habitats (≤ 50 m).
Pressure	**Proposed benchmark(s)**
Ocean acidification	**Middle emission scenario benchmark:** a further decrease in pH of 0.15 (annual mean) and corresponding 35% increase in H+ ions with no coastal aragonite undersaturation and the aragonite saturation horizon in the NE Atlantic, off the continental shelf, at a depth of 800 m by the end of this century (2081-2100) **High emission scenario benchmark:** a further decrease in pH of 0.35 (annual mean) and corresponding 120% increase in H+ ions , seasonal aragonite saturation of 20% of UK coastal waters and North Sea bottom waters, and the aragonite saturation horizon in the NE Atlantic, off the continental shelf, occurring at a depth of 400 m by the end of this century (2081-2100)
	Pressure description
	Increased CO_2 concentrations in the atmosphere are absorbed by the ocean. Increased CO_2 concentrations affect the carbonate chemistry of seawater, and result in a reduction in pH, changes in the carbonate saturation and, potentially, hypercapnia (CO_2 poisoning) in marine organisms. Increasing levels of CO_2 in the atmosphere have led to the average pH of sea surface waters dropping from 8.25 in the 1700s to 8.14 in the 1990s, leading to a 25% increase in H^+ ions (Jacobson, 2005). However, The pH of surface waters are highly variable over time (Fig. 5), which reflects seasonal cycles in photosynthesis, respiration and water mixing (Ostle *et al.*, 2016). Marine calcifiers may be particularly at risk, especially as waters suffer from seasonal aragonite undersaturation, leading to dissolution of calcium carbonate. Aragonite saturation state is influenced by dissolved inorganic carbon (DIC) concentration, pressure and temperature so that deep waters, which have high levels of DIC, high pressure and low temperatures, will be the first habitats to face undersaturation (C. Ostle *pers. comm.*).

Pressure	Proposed benchmark(s)
Sea-level rise	**Middle emission scenario benchmark**: a 50 cm rise in average UK sea-level rise by the end of this century (2081-2100). **High emission scenario benchmark:** a 70 cm rise in average UK by the end of this century (2018-2100). **Extreme scenario benchmark:** a 107 cm rise in average UK by the end of this century (2018-2100).
	Pressure description
	Sea-level rise results from a combination of the thermal expansion of seawater and ice melt (e.g. ice sheets and glaciers). Sea-levels have risen 1-3 mm/yr in the last century (Cazenave & Nerem, 2004, Church *et al.*, 2004, Church & White, 2006). The global mean sea-level has risen by 0.16 m (a range of 0.12-0.21 m) between 1902 and 2015 (IPCC, 2019). The rate of rise in 2006-2015 is unprecedented compared to the last century, during which period sea-level rise has been dominated by melting ice-sheets and glaciers (IPCC, 2019). A rise in sea-level increases the water depth at the shore and results in increased wave and tidal energy along the shore, due to the increase in fetch and reduction in wave attenuation (Pethick, 2001; Crooks, 2004; Fujii, 2012). As a result, coastal landforms (e.g. subtidal bedforms, intertidal flats, saltmarshes, shingle banks, sand dunes, cliffs and coastal lowlands) migrate along and parallel to the shore to maintain their position with the coastal energy gradient (Crooks, 2004; Fujii, 2012). Sedimentary habitats are dynamic and liable to adapt to sea-level rise, except where hard structures (e.g. cliffs and artificial structures) prevent their natural movement, where existing intertidal areas are likely to be submerged, eroded, or moved (coastal-squeeze).

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