

# Ocean Acidification around the UK and Ireland

Findlay, H.S.<sup>1</sup>, Artoli, Y.<sup>1</sup>, Birchenough, S.N.R.<sup>3</sup>, Hartman, S.<sup>4</sup>, León, P.<sup>5</sup> and Stiasny, M.<sup>6</sup>

<sup>1</sup> Plymouth Marine Laboratory, West Hoe, Plymouth, PL1 3DH, UK.

<sup>3</sup> The Centre for Environment, Fisheries and Aquaculture (Cefas), Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk, NR 33 0HT, UK.

<sup>4</sup> National Oceanography Centre Southampton, European Way, Southampton, SO14 3ZH, UK.

<sup>5</sup> Marine Scotland Science, Marine Laboratory, 375 Victoria Road, Aberdeen, AB11 9DB, UK.

<sup>6</sup> University of Southampton, School of Ocean and Earth Science, University Road, Southampton, SO17 1BJ

## KEY FACTS

### What is already happening

- Atmospheric CO<sub>2</sub> exceeded 414 ppm in 2021 and has continued to increase by approximately 2.4 ppm per year over the last decade. The global ocean absorbs approximately a quarter of anthropogenic carbon dioxide (CO<sub>2</sub>) emissions annually.
- The North Atlantic Ocean contains more anthropogenic CO<sub>2</sub> than any other ocean basin, and surface waters are experiencing an ongoing decline in pH (increasing acidity). Rates of acidification in bottom waters are occurring faster at some locations than in surface waters.
- Some species are already showing effects from ocean acidification when exposed to short-term fluctuations and could be used as indicator species for long-term impacts on marine ecosystems.

### What could happen in the future

- Models project that the average continental shelf seawater pH will continue to decline to year 2050 at similar rates to the present day, with rates then increasing in the second half of the century, depending on the emissions scenario.
- The rate of pH decline in coastal areas is projected to be faster in some areas (e.g. Bristol Channel) than others, such as the Celtic Sea.
- Under high-emission scenarios, it is projected that bottom waters on the North-West European Shelf seas will become corrosive to more-soluble forms of calcium carbonate (aragonite). Episodic undersaturation events are projected to begin by 2030.
- By 2100, up to 90% of the north-west European shelf seas may experience undersaturation for at least one month of each year.
- High levels of nearshore variability in carbonate chemistry may mean that some coastal species have a higher adaptive capacity than

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others. However, all species are at increased risk from extreme exposure episodes.

## SUPPORTING EVIDENCE

### Introduction

#### *CO<sub>2</sub> uptake and acidification*

The average atmospheric carbon dioxide (CO<sub>2</sub>) concentration exceeded 414 parts per million (ppm) in 2021, a 49 % increase above pre-industrial levels, and increasing on average by 2.4 ppm per year over the past decade (Friedlingstein *et al.*, 2022). This ongoing increase is primarily due to CO<sub>2</sub> release by fossil fuel combustion, cement production and land-use change (mainly deforestation) (Friedlingstein *et al.*, 2022; IPCC, 2021). Over a quarter of this annual anthropogenic CO<sub>2</sub> emission dissolves into the Earth's oceans each year (fossil fuel CO<sub>2</sub> emissions =  $9.5 \pm 0.5$  gigatonnes of carbon per year (Gt C yr<sup>-1</sup>, 1 Gt = one thousand million tonnes)), Land-use change emissions =  $1.1 \pm 0.7$  Gt C yr<sup>-1</sup>, ocean uptake =  $2.8 \pm 0.4$  Gt C yr<sup>-1</sup>; Friedlingstein *et al.*, 2022). Once dissolved, the CO<sub>2</sub> no longer influences the atmospheric heat budget, so this oceanic uptake mitigates human-driven warming and climate change. However, dissolved (or aqueous) CO<sub>2</sub> undergoes a chemical reaction that releases hydrogen ions (H<sup>+</sup>), thereby decreasing the seawater's pH (Figure 1). As pH declines, the carbonate ion concentration ([CO<sub>3</sub><sup>2-</sup>]) also declines (Figure 1). The [CO<sub>3</sub><sup>2-</sup>] controls the saturation state ( $\Omega$ ) of calcium carbonate (CaCO<sub>3</sub>) minerals such as aragonite ( $\Omega_{Arag}$ ) and calcite ( $\Omega_{Cal}$ ), and indicates the ability of these minerals to precipitate (form) or dissolve. At  $\Omega > 1$  water is supersaturated with Ca<sup>2+</sup> and CO<sub>3</sub><sup>2-</sup> ions allowing CaCO<sub>3</sub> minerals to form. When  $\Omega < 1$ , seawater is undersaturated with Ca<sup>2+</sup> and CO<sub>3</sub><sup>2-</sup> ions and therefore any exposed CaCO<sub>3</sub> minerals are prone to dissolution. These collective changes in marine carbonate chemistry are known as 'ocean acidification'.

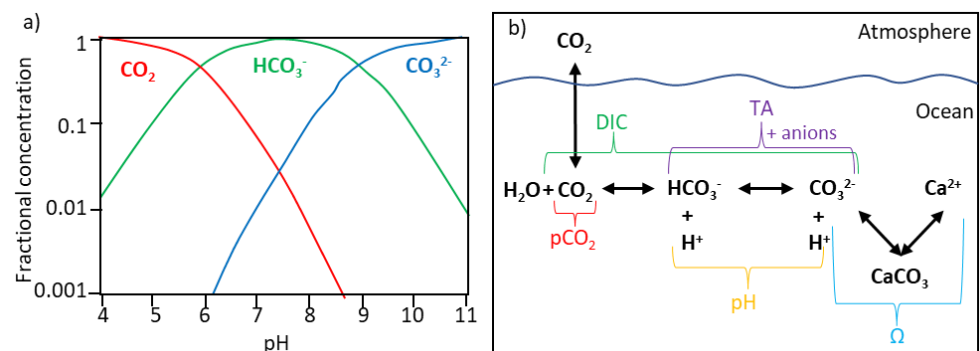


Figure 1: (a) Relationship between seawater pH and the relative concentrations of the constituents that make up total Dissolved Inorganic Carbon (DIC). These constituents are: aqueous CO<sub>2</sub>, bicarbonate ions (HCO<sub>3</sub><sup>-</sup>) and carbonate ions (CO<sub>3</sub><sup>2-</sup>). At typical seawater pH, a little over 8, about 90% of DIC is in the HCO<sub>3</sub><sup>-</sup> form, about 10% is CO<sub>3</sub><sup>2-</sup>, and <1% is aqueous CO<sub>2</sub>. Adding more CO<sub>2</sub> increases its relative concentration, shifting the system to lower pH, and thus decreases the abundance of CO<sub>3</sub><sup>2-</sup>. (After Raven *et al.*, 2005). (b) Schematic of the carbonate system in seawater, highlighting which parts

of the system are included in dissolved inorganic carbon (DIC), total alkalinity (TA), partial pressure of CO<sub>2</sub> (pCO<sub>2</sub>), and saturation state (Ω), respectively.

Global observations and model statistical calculations determining probable past conditions show that up to year 2000, ocean acidification already had caused a decrease in average global surface water pH by 0.1 unit, or become 30 % more acidic compared to pre-industrial levels (IPCC, 2021). Within the past decade, pH has continued to decline on a global average scale of about 0.0016 y<sup>-1</sup> (E.U. Copernicus Marine Service Information, DOI (product): <https://doi.org/10.48670/moi-00224>), such that the in year 2020 the surface ocean was approximately 40 % more acidic than pre-industrial levels. Trends for increasing seawater CO<sub>2</sub> and decreasing pH are now routinely observed at long-term oceanographic time-series recording stations across the world (Bates *et al.*, 2014). Global analysis suggests that for 95 % of the ocean surface area, the decline in pH has very likely already emerged from background natural variability (IPCC, 2019).

### ***Implications for biological and biogeochemical systems***

This paper focusses primarily on the physicochemical changes related to ocean acidification. The biological, biogeochemical, and wider societal impacts of ocean acidification are dealt with in the MCCIP impact reviews. Here the potential implications are briefly discussed at a broad level. In the following sections only recent studies that are specific to the European shelf-sea region are highlighted.

Ocean acidification can influence marine species in a number of ways, including direct impacts on internal physiology from the changes in pH and pCO<sub>2</sub> of the surrounding seawater or indirectly through changes to food webs and processes (Birchenough *et al.*, 2015; Findlay and Turley, 2021). Ocean acidification can have positive, neutral or negative impacts depending on the process, population, or species that is being investigated (Kroeker *et al.*, 2013). Many phytoplankton, seaweeds and algae species, for instance, show a positive or neutral response to elevated CO<sub>2</sub> (Dutkiewicz *et al.*, 2015; Kroeker *et al.*, 2013). However, for marine invertebrates and some fish species, the direct response to lowered pH and elevated CO<sub>2</sub> is generally either neutral or negative (Kroeker *et al.*, 2013). In addition to the direct physiological impact, those species that build their skeletons or structures from CaCO<sub>3</sub> minerals, such as corals, shellfish, and several important groups of plankton (Doney *et al.*, 2020) are at increased risk from ocean acidification if these structures become exposed to waters containing lower CaCO<sub>3</sub> levels. More developed organisms, such as fish, may be less susceptible to direct impacts, but loss of key prey species could impact them indirectly (Le Quesne and Pinnegar, 2012). Recent efforts of combining several approaches to ‘scale-up impact’ (from experiments to biogeochemical models) have demonstrated the need to better planning and integration of scales (Townhill *et al.*, 2022).

Biogeochemical cycling also has the potential to be impacted by ocean acidification (Findlay and Turley, 2021), as changes in pH and CO<sub>2</sub> have been shown to impact numerous process including carbon cycling and uptake, metal speciation (Zhu *et al.*, 2021; Breitbarth *et al.*, 2010), nutrient cycling (e.g. Wannicke *et al.*, 2018), and production of climatically-important gases (e.g. Hopkins *et al.*, 2020; Campen *et al.*, 2022).

## WHAT IS ALREADY HAPPENING?

### *Open ocean – wider Atlantic region/deep waters*

Regardless of where it is emitted, anthropogenic CO<sub>2</sub> is mixed throughout the Earth's atmosphere by wind and weather. The increasing amount of CO<sub>2</sub> taken up by the oceans and corresponding pH decline are therefore global phenomena (McKinley *et al.*, 2017). Landschützer *et al.* (2016) mapped global surface ocean fCO<sub>2</sub> (fugacity of CO<sub>2</sub>; a thermodynamic way of expressing the partial pressure of CO<sub>2</sub> (pCO<sub>2</sub>)) from 1982 to 2011 using a neural network approach. They found that the annual global net oceanic CO<sub>2</sub> sink was variable on decadal timescales, with a range from about 0.8 to 2.0 Gt of carbon per year ; Friedlingstein *et al.*, (2022) reported on the global carbon budget and calculated an average ocean uptake over the past decade of 2.8 Gt C yr<sup>-1</sup>. Changing patterns of sea-surface temperature, themselves likely to be a consequence of climate change, have been shown to drive an important component of this decadal variability in ocean CO<sub>2</sub> uptake (Landschützer *et al.*, 2016).

The magnitude of the seasonal cycle of sea surface fCO<sub>2</sub> has also increased between the 1980s and present day, driven by stronger seasonal cycles in fCO<sub>2</sub> drivers (e.g. temperature), augmented by the lower chemical buffer capacity of seawater at higher fCO<sub>2</sub> due to ocean acidification (Watson *et al.*, 2020; Landschützer *et al.*, 2018). This phenomenon of increased seasonality over time has also been observed at the regional scale around the North-East Atlantic: The Porcupine Abyssal Plain Sustained Observatory (PAP-SO) in the North Atlantic is one of the few open ocean fixed-observatories measuring surface pCO<sub>2</sub> year-round (Hartman *et al.*, 2021; Heiskanen *et al.*, 2021). Macovei *et al.*, (2020) combined PAP-SO observatory and ship of opportunity measurements, and found that although the annual mean seawater pCO<sub>2</sub> did not increase between the period 2002 to 2016, there was an increase in the seasonality (i.e. the difference in fCO<sub>2</sub> between winter and summer) over time, demonstrating that the region has continued to absorb atmospheric CO<sub>2</sub> in recent years, and that this CO<sub>2</sub> sink has enhanced over this period.

As surface waters are in direct contact with the atmosphere it is this layer that has been the focus of primary concern with respect to ocean acidification. Ship-based observations show that ocean acidification has been, and is, occurring in the wider North Atlantic Ocean. For example, data for the south Rockall Trough section to the west of the Irish shelf compared with WOCE

surveys from the 1990s suggests a pH decline of about 0.02 per decade in the surface waters (McGrath *et al.*, 2012). Data from the Autumn (southbound) AMT cruises suggests the whole Atlantic has seen a decrease in ocean pH (mean  $-0.0013 \pm 0.0009 \text{ yr}^{-1}$ ) with some areas in the North East Atlantic ( $>40 \text{ N}$ ) observing pH rates faster than  $-0.002 \text{ yr}^{-1}$  (Kitidis *et al.*, 2017), and matching data from Rockall. Data from around Iceland shows rates of acidification in the surface waters of  $-0.0021$  to  $-0.0033 \text{ pH unit yr}^{-1}$  and a decline in  $\Omega_{\text{Arag}}$  of  $-0.006$  to  $-0.012 \text{ yr}^{-1}$  (Olafsson *et al.*, 2009), while data from the open ocean sub-Arctic region shows surface pH declines of  $-0.0033 \text{ yr}^{-1}$  at station OWS M in the Norwegian Sea (Skjelvan *et al.*, 2022) based on nearly three decades of observations. Fransner *et al.*, (2022) found rates to vary across the basins of the Nordic Seas ( $-0.0017$  and  $-0.0031 \text{ yr}^{-1}$ ) based on nearly four decades of observations. These negative surface pH trends found in the Nordic Seas have been directly attributed to increases in dissolved inorganic carbon resulting from uptake of  $\text{CO}_2$  from the atmosphere (Skjelvan *et al.*, 2022; Fransner *et al.*, 2022). However, in specific regions, such as the Barents Sea Opening, changes in total alkalinity through increasing Atlantic water inflow also play a role (Jones *et al.*, 2020; Skjelvan *et al.*, 2021).

While primarily considered a surface-water issue, ocean acidification is also spreading throughout the water column. The North Atlantic ocean contains more anthropogenic  $\text{CO}_2$  than any other ocean basin, due to deep-water formation that occurs there, which effectively transfers  $\text{CO}_2$  from the surface into the ocean interior (Sabine *et al.*, 2004; Khatiwala *et al.*, 2013). While North Atlantic deep-water formation is climatically beneficial in terms of exporting  $\text{CO}_2$  from the surface into the interior ocean, Pérez *et al.* (2018) showed that it also causes ocean acidification at depth. In addition to this physical pumping of anthropogenic carbon to the deep water, there are a number of other key processes that result in intermediate and deep waters having elevated carbon and lower pH compared to the surface waters. Vertical stratification (layering) between the surface and deep water can limit the exchange of carbon resulting in a build-up in deep waters, which is associated with lower pH in these deep-water masses. Vertical stratification has been shown to be increasing in response to global climate change, which results in an additional decrease in deep water pH in some regions (Chen *et al.*, 2017). As organic matter sinks to intermediate depths and beyond, there is an intensified remineralisation, which results in release of carbon into the water and this again enhances ocean acidification (García-Ibáñez *et al.*, 2016).

Numerous observations across the North Atlantic, using repeat transects or time-series stations, are now showing changes in ocean chemistry in the interior ocean that reflect increasing ocean acidification (OSPAR, 2022). In the Irminger Sea and Iceland Sea there is particular rapid acidification in the interior ocean, and this has been previously highlighted (Olafsson *et al.*, 2009; García-Ibáñez *et al.*, 2016; Pérez *et al.*, 2018, 2021; Vázquez-Rodríguez *et al.*, 2012), while data from the UK's Extended Ellett Line transect between

Scotland and Iceland also shows increases in inorganic carbon at depth (Humphreys *et al.*, 2016). The consequences of ocean acidification are therefore not restricted to the surface ocean, but based on experimental work, have the potential to impact marine species and ecosystems at greater depths, such as cold-water coral reefs, which occur around the UK shelf and north-east Atlantic at depths from 200 m to 1500 m (Hoegh-Guldberg *et al.*, 2017; Fontela *et al.*, 2020).

### ***Shelf seas around the UK***

The seawater chemistry in shallow (<200 m) continental shelf seas like those surrounding the UK is generally more variable in space and time than in the open ocean, as it is driven by a more complex set of processes (including terrestrial influences) operating on smaller spatial scales (Carstensen and Duarte, 2019). Indeed, data for  $f\text{CO}_2$  taken from observations around the North-West European Shelf (NWES) seas have shown that variability increases from 100-200  $\mu\text{atm}$  in locations sampled further than 300 km offshore, to >300  $\mu\text{atm}$  within about 10 km of land (Figure 2). There is also a strong seasonal signal in  $f\text{CO}_2$  observable in the Celtic Sea, Irish Sea and northern North Sea (Figure 3). During the spring and summer months biological activity (photosynthesis) captures  $\text{CO}_2$  in the stratified surface layer, which then gets transported into deeper waters. During autumn and winter, the stratification breaks down, and  $\text{CO}_2$  that has been produced at depth through respiration and remineralisation is mixed throughout the water column causing a peak in  $f\text{CO}_2$  during winter. There are exceptions, for example in the southern bight of the North Sea and eastern English Channel thermally-driven increases in  $f\text{CO}_2$  occur in summer (Figure 3; Hartman *et al.*, 2019), which is primarily retained throughout the year since the water column in this relatively shallow and does not stratify (Thomas *et al.*, 2004). In these areas close to rivers along the French coast, there are also large fluctuations in  $f\text{CO}_2$  during periods of greatest river flow (Figure 3). As  $\text{CO}_2$  is a major driver for pH change and ocean acidification, the dynamics of the pH correspond to  $f\text{CO}_2$ , such that when  $\text{CO}_2$  is taken up and is at high levels in the water, pH is reduced. While pH measurements are much less frequently gathered, in-situ observations show similar patterns in seasonal cycle and variability around the NWES seas (Figure 4).

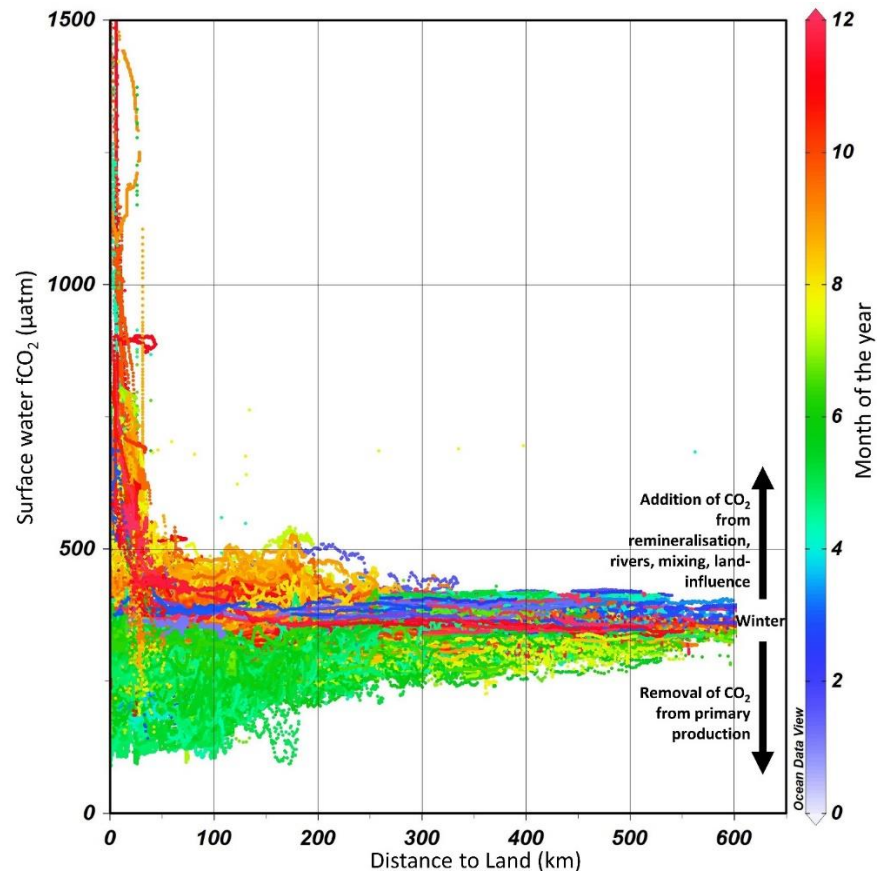


Figure 2: fCO<sub>2</sub> from SOCATv.2021 for North-West European Shelf Sea region (see map of data points in Figure 3) in relation to distance to land (km). Colour bar represents the continuous time with respect to month of the year. Data are from year 2010 to 2020. Arrows illustrate the processes that increase or decrease CO<sub>2</sub> from the winter value.

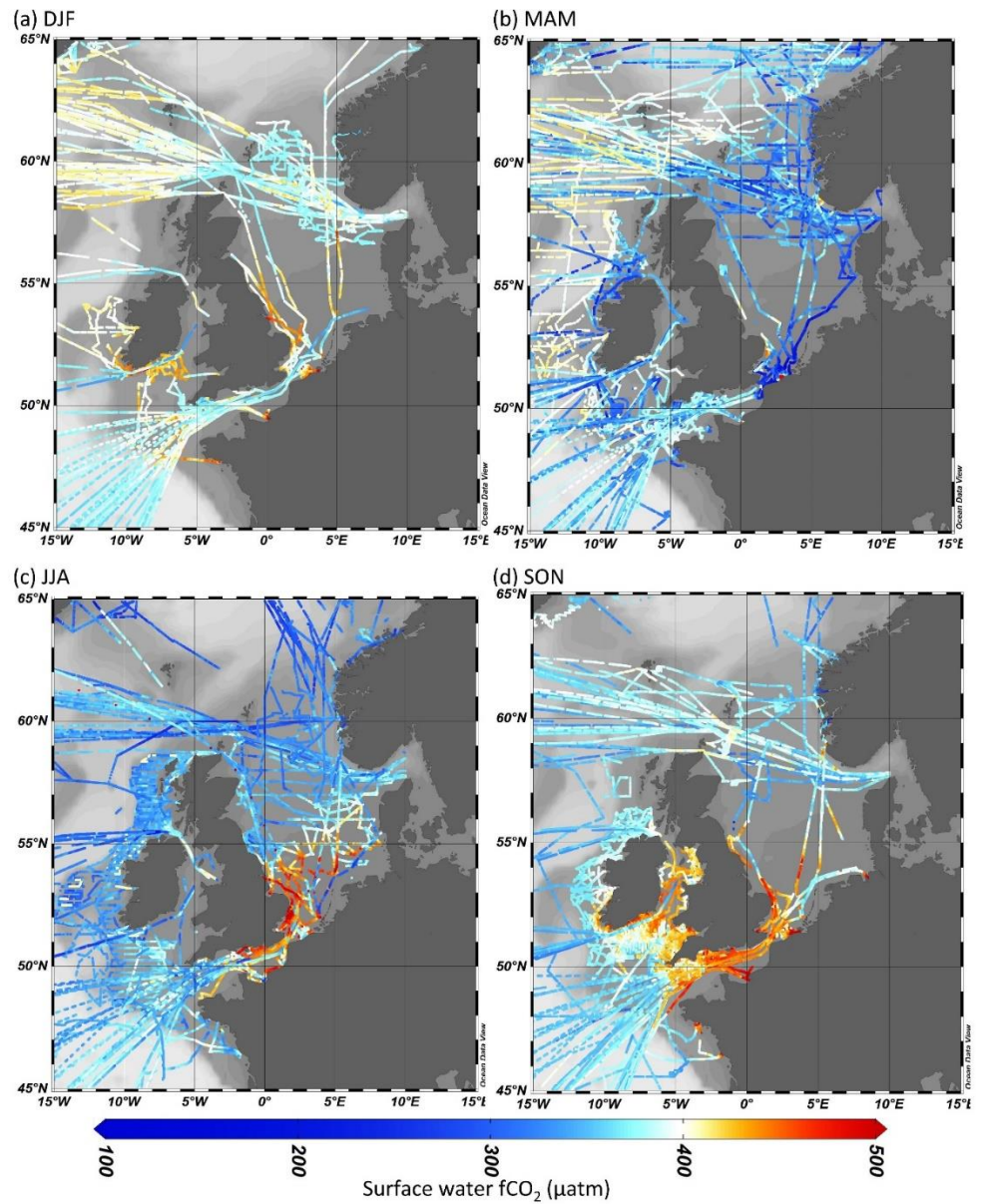


Figure 3: Surface water  $f\text{CO}_2$  between years 2010 and 2020 from SOCATv.2021 for the North-West European Shelf Seas separated by season (a) winter – December, January, February (DJF); (b) Spring – March, April, May (MAM); (c) Summer – June, July, August (JJA); (d) Autumn – September, October, November (SON).



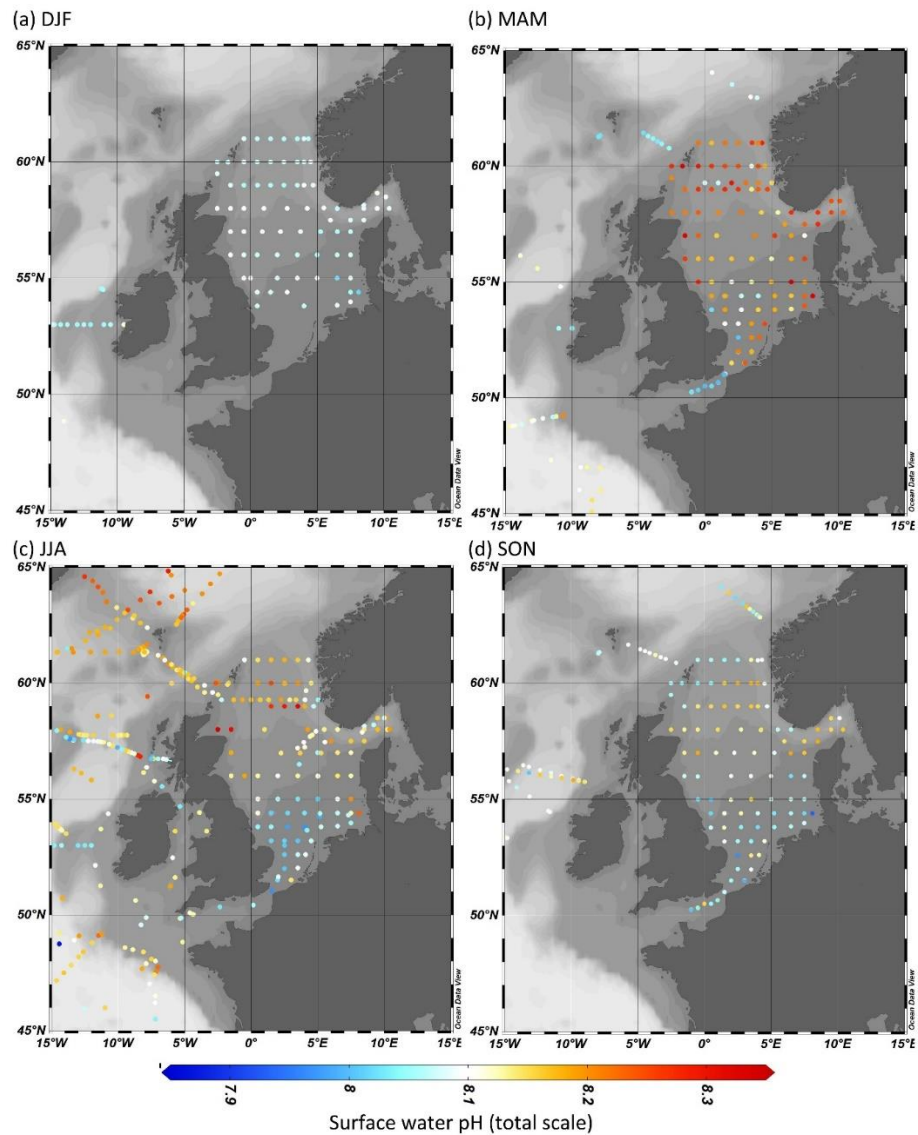


Figure 4: Surface water pH between years 2010 and 2020 from GLODAPv2.2021 for the North-West European Shelf Seas separated by season (a) winter – December, January, February (DJF); (b) Spring – March, April, May (MAM); (c) Summer – June, July, August (JJA); (d) Autumn – September, October, November (SON).

Although spatially there is a reasonable understanding of the carbonate chemistry dynamics around the NWES seas, the data is sparse through time, preventing the production of a time-series assessment at this scale. However regional models can provide hindcast projections to fill these gaps. The AMM7 (Atlantic Margin Model at 7 km) is a model based on the ocean dynamic model NEMO (Nucleus for European Modelling of the Ocean (Madec and team, 2016) and ERSEM (Butenschön *et al.*, 2016), a biogeochemical model that describes the cycling of the major elements (carbon, nitrogen, phosphorus and silicon) across the planktonic food web and its effect on the dynamics of the carbonate system.

The DARE-UK project (<https://dareuk.blogs.bristol.ac.uk/>) used the AMM7 NEMO-ERSEM to run hindcasts from 1990 to 2015. During this period surface water pH has declined by an average of about  $-0.002 \text{ pH units yr}^{-1}$ ,

with some spatial variation in this trend (Figure 5a). The bottom waters on the shelf region (water depth <200 m) have also seen similar rate of decline, although in some areas, for example south and west of Ireland and central to north-eastern North Sea, the model suggests there has been faster rates of decline ( $-0.005$  pH units  $\text{yr}^{-1}$ ; Figure 5b). The model highlights that there is larger interannual variability in these shallow shelf seas and that ocean acidification is occurring throughout the water column (OSPAR, 2022).

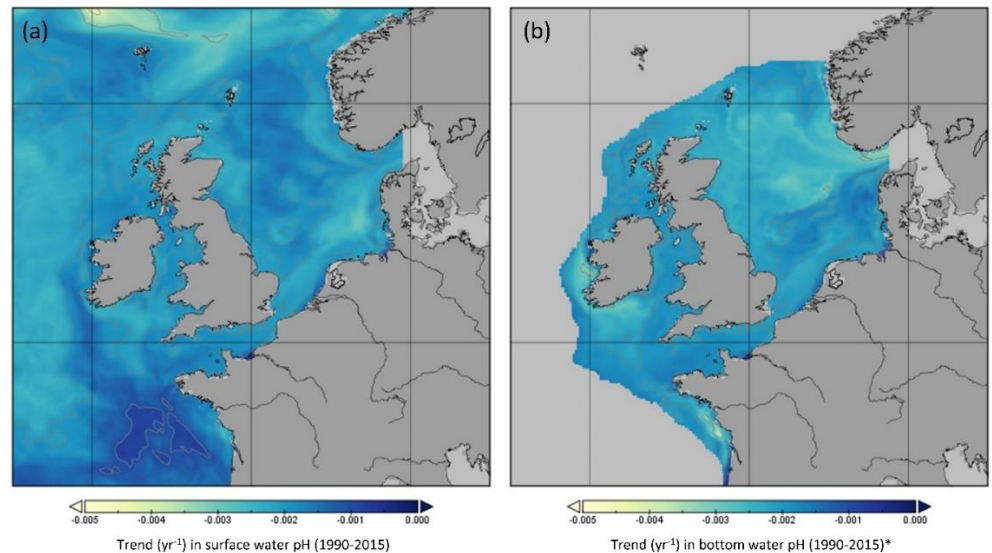


Figure 5: NEMO-ERSEM Model hindcast pH trend projections for the period 1990-2015 for (a) surface waters and (b) bottom waters (\* where water depth is <200 m).

### ***Near-shore coasts – long-term stations Stonehaven & Western Channel Observatory***

As is highlighted by the SOCAT  $f\text{CO}_2$  data, the nearshore/ coasts potentially experience a much greater variability in carbon dynamics than offshore and open ocean locations. Around the UK there are very few observations that provide the long-term, high frequency data needed to quantify the processes driving this variability. The two main carbon time-series recorders in the UK are Marine Science Scotland’s Stonehaven station, located about 5 km off the east coast of Scotland, and Plymouth Marine Laboratory’s Western Channel Observatory station L4 located about 7 km off the south-west coast of England (map in Figure 6). The carbonate system parameters have been measured weekly (conditions permitting) since the end of 2008 at both these sites (noting that although Stonehaven has samples collected from 2015 onwards, this data is not yet available).

Both stations show seasonal dynamics in the carbonate system driven by a combination of temperature and biological activity (higher [lower] autumn/winter  $f\text{CO}_2$  [pH] and lower [higher] spring/summer  $f\text{CO}_2$  [pH]), Figure 6). However there is also significant annual variation, especially at WCO L4 where the nearby rivers, as well as tidal dynamics and mixing, are known to contribute to the variability (Sims *et al.*, 2022). Despite this weekly, seasonal, and annual variability, significant trends of increasing  $f\text{CO}_2$  and

decreasing pH have been found in both datasets (Figure 7). The longer WCO L4 time-series records show an increase in  $f\text{CO}_2$  of  $6.4 \mu\text{atm yr}^{-1}$  and a decrease in pH of  $-0.006 \text{ yr}^{-1}$ . The shorter Stonehaven time-series shows faster rates of  $f\text{CO}_2$  increase and pH decrease ( $19.3 \mu\text{atm yr}^{-1}$  and  $-0.018 \text{ yr}^{-1}$ , respectively; Figure 7), which are likely to be due to these shorter-term dynamics, and as highlighted by describing the trend for the same period from the WCO L4 timeseries (Figure 7). The WCO L4 decline in pH is a faster rate than found in the hindcast model. Nearshore and coastal stations samples for  $>10$  years across the Dutch and French coasts confirm these faster rates of acidification in the nearshore, with greatest observed rates of pH decline of  $-0.02 \text{ yr}^{-1}$  in some of these regions (OSPAR, 2022).

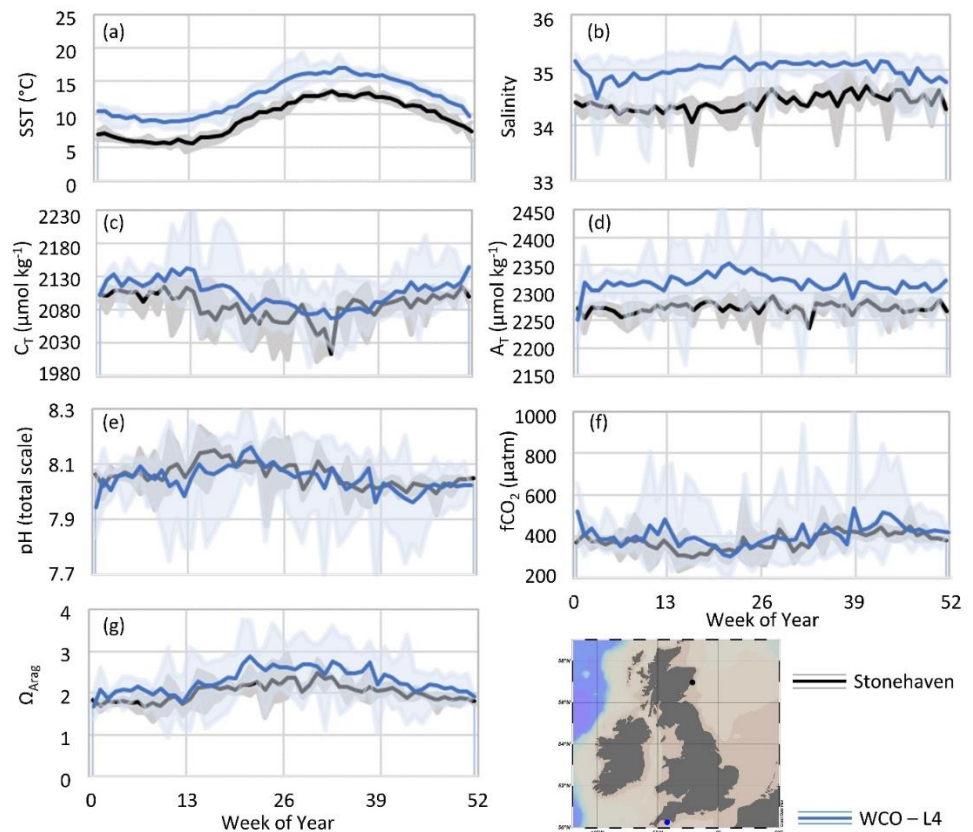


Figure 6: Seasonal cycle at stations Stonehaven (black and grey lines) and WCO L4 (blue lines) for surface water (a) temperature (SST), (b) salinity, (c) dissolved inorganic carbon (CT), (d) total alkalinity (AT), (e) calculated pH, (f) calculated  $f\text{CO}_2$ , (g) calculated aragonite saturation state. Thick lines are mean values, thin lines represent maximum and minimum values, data are from full time-series periods (2008 – 2014 Stonehaven; 2008 – 2021 WCO L4).

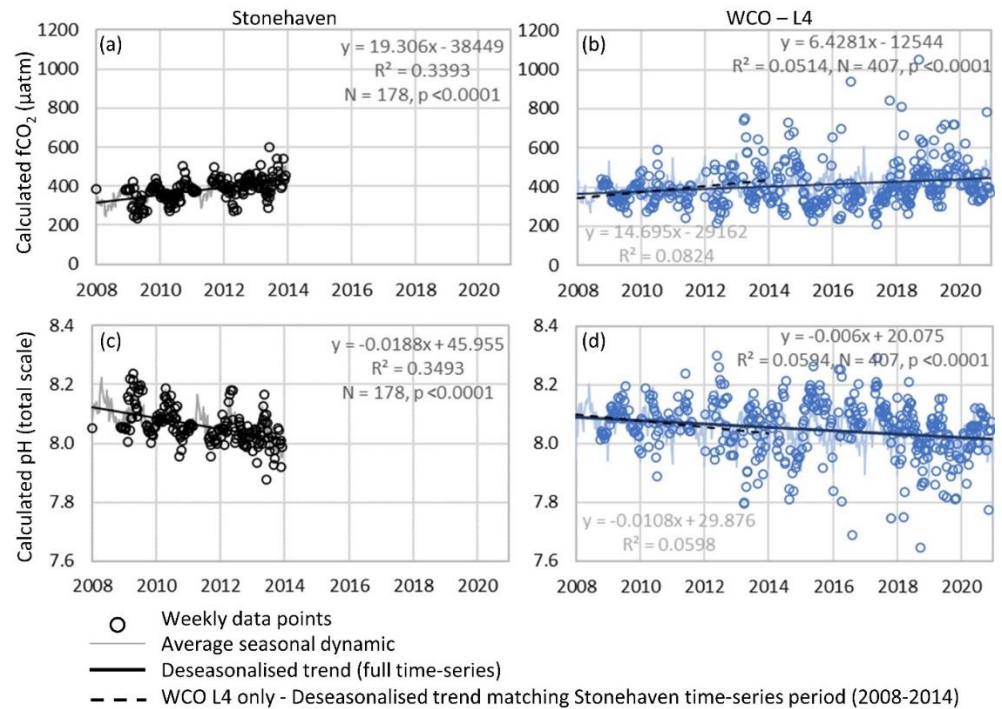


Figure 7: Time-series data (open circles) for Stonehaven (a and c) and WCO L4 (b and d) showing surface water  $f\text{CO}_2$  (a and b) and pH (c and d). Both values are calculated from measured dissolved inorganic carbon and total alkalinity. The average seasonal fit is shown as the thin line; deseasonalised trends for each full time-series are shown as thick lines. In addition, on the WCO L4 time-series deseasonalised trends are shown in dashed lines using the same time period as the Stonehaven data.

### Biological impacts

As discussed briefly in the introduction, ocean acidification has the potential to alter ecosystems in a variety of ways, depending on the characteristics of the systems and the species (see Birchenough *et al.*, 2017 for details of variability and species studied in the UK). To date, there is limited evidence of ocean acidification impacting marine organisms or processes around the UK and north-east Atlantic, outside of laboratory or mesocosm experiments. This is primarily due to the lack of data whereby biological change can be attributed to changes in chemistry. However, this is also in part due to the level of acidification presently experienced, such that around the NWES region there are few areas that have reached levels of acidification that may cause direct observable change in ecosystems. The lack of co-located multidecadal chemical and biological time-series measurements makes it difficult to link observed changes in biology to ocean acidification, especially as ocean acidification is just one of a suite of pressures driving change (Beaugrand *et al.*, 2013). Only in the coming decades as monitoring continues, and depending on continued rates of acidification, are impacts likely to become more apparent.

Where biological and chemical observations do coexist, more detailed assessments can be made. The evidence that is available highlights that species, particularly calcified species, can be used as indicators for ocean acidification (Bednaršek *et al.*, 2019), as short-term variability in carbonate

parameters is already causing observable impacts on individuals. For example, a recent 3-year study in the northern North Sea supports the relationship between natural variability in seawater  $\Omega_{\text{Arag}}$  and shell integrity in pelagic gastropods (León *et al.*, 2020). By examining specimens collected at the Scottish Coastal Observatory monitoring site at Stonehaven, the study revealed sustained evidence of shell dissolution (corrosion) under aragonite supersaturated conditions, with the most severe shell damage observed during winter coinciding with periods of lowest  $\Omega_{\text{Arag}}$ . A similar analysis on bivalve larvae specimens collected at Stonehaven during the same study period (León *et al.*, in prep.) shows evidence of shell dissolution matching that temporal pattern but also suggesting a greater vulnerability of bivalve larvae to changes in seawater  $\Omega_{\text{Arag}}$  than in the pelagic gastropods (OSPAR, 2022). Although consistent longer time-series records are required to calculate robust accurate trends, these findings support previous observations suggesting that seasonal and short-term changes in  $\Omega_{\text{Arag}}$ , rather than only absolute thresholds (León *et al.*, 2020), might affect the shell integrity of plankton calcifiers. The vulnerability of bivalve early-life stages together with projected future ocean acidification scenarios for the region, raise concern on the potential consequences for bivalve and crustacean populations in the North Sea and for future implications for the shellfish and aquaculture industry (Mangi *et al.*, 2018).

## WHAT COULD HAPPEN IN THE FUTURE?

### *Model forecasts*

The following figures and discussion are based on modelling results provided for the OSPAR Quality Status Review Ocean Acidification Assessment (OSPAR, 2022), which use the AMM7 that has been used for the hindcast projections described above. For these future projections the main temporal horizon used is the mid-century (about year 2050) to focus on the more immediate risks and a mid- emission scenario (RCP4.5) and a high emission scenario (RCP8.5) have been used. Some consideration on the longer time (~2100) is also provided, for the higher emission scenario. Global mitigation efforts aligning to the Paris Agreement of limiting global warming to 1.5 to 2°C, mean that the RCP8.5 scenario is now less likely. Current policies to reduce greenhouse gas emissions suggest the world is on track for a warming scenario of between 2 and 3.6°C (Climate Action Tracker), which is between RCP3.6 (warming between 1.8 and 3.8°C) and RCP4.5 (warming between 2 and 4.3°C).

The AMM7 projects pH decreasing at a mean rate of  $-0.002 \text{ yr}^{-1}$  under RCP4.5 and  $-0.003 \text{ yr}^{-1}$  under RCP8.5 from present until 2050 (Figure 8). Significant spatial variability in the rate of pH decline is projected, with changes as fast as  $-0.005 \text{ yr}^{-1}$  (RCP8.5) in some coastal areas like the Bristol Channel and the West coast of Denmark, and as slow as  $-0.002 \text{ yr}^{-1}$  (RCP8.5) in the Celtic Sea (OSPAR, 2022). The projected spatial patterns of surface  $\text{CaCO}_3$  mineral saturation state matches that for pH (Figure 8). The AMM7

model projects aragonite undersaturation of surface waters in the Norwegian Current towards the end of this century. However, the uncertainty in projections for this region is relatively high due to the strong influence of water influxes from the Baltic Sea, which are poorly constrained (OSPAR, 2022).

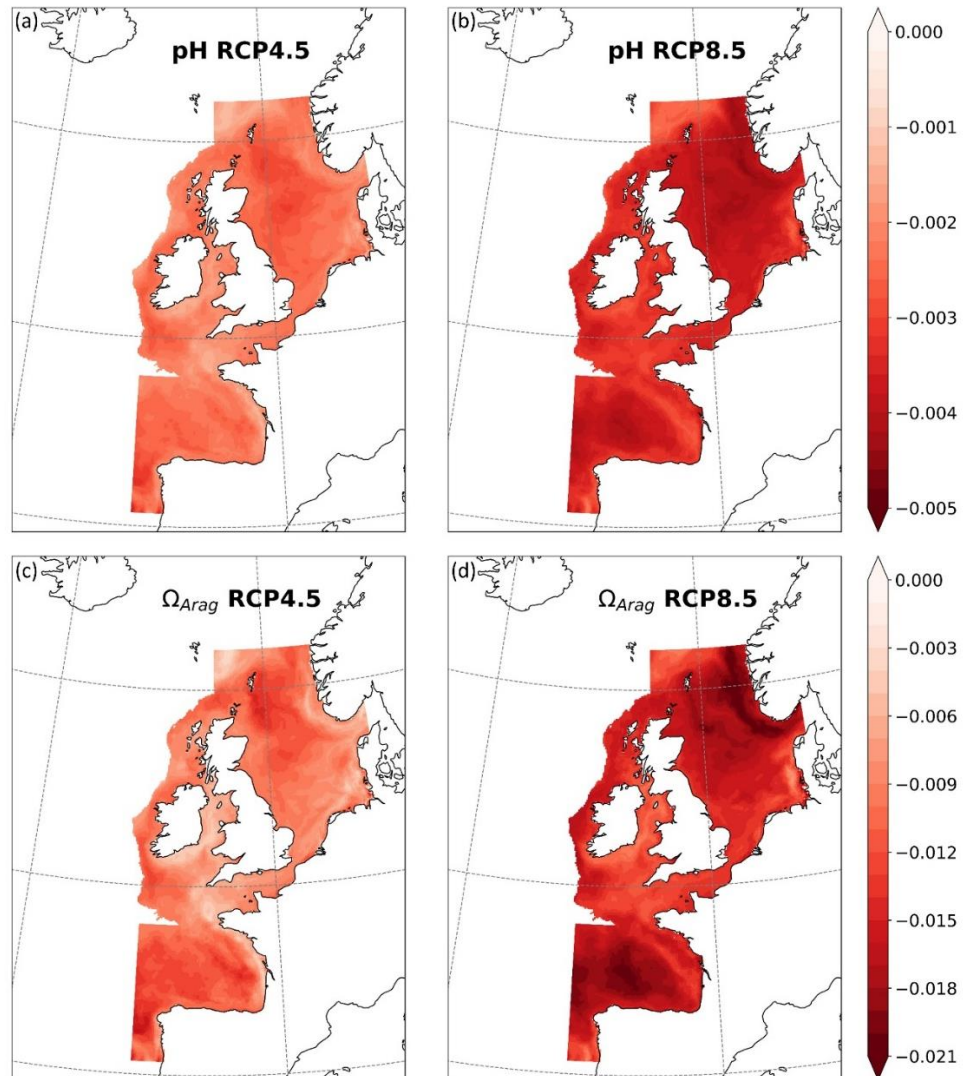


Figure 8: Trend of surface pH (top; yr<sup>-1</sup>) and Ω<sub>Arag</sub> (bottom; yr<sup>-1</sup>) between 2050 and 2000 as projected by the AMM7-NEMO-ERSEM model under the RCP 4.5 scenario (left) and RCP8.5 scenario (right). Only data within the OSPAR regions II, II and IV has been shown. (OSPAR, 2022.)

On the shelf (water depth <200 m), the bottom waters around the UK are projected to experience faster rates of decline in pH and Ω<sub>Arag</sub> because of the seasonal processes that influence the carbonate chemistry at depth that can exacerbate the global ocean acidification signal. For example, the average trends of pH in bottom waters in the Greater North Sea are between -0.0027 yr<sup>-1</sup> (RCP4.5) and -0.0040 yr<sup>-1</sup> (RCP8.5) between 10 % and 15% more rapid than at surface (Figure 9). This difference is particularly evident in the central and northern part of the North Sea where stratification is more important. The average trends of Ω<sub>Arag</sub> are between -0.0100 yr<sup>-1</sup> (RCP4.5) and -0.0145 yr<sup>-1</sup> (RCP8.5) and the spatial pattern is similar to the one of pH, with pHΩ<sub>Arag</sub>

decline being more rapid in the Northern North Sea and close to the shelf break (OSPAR, 2022).

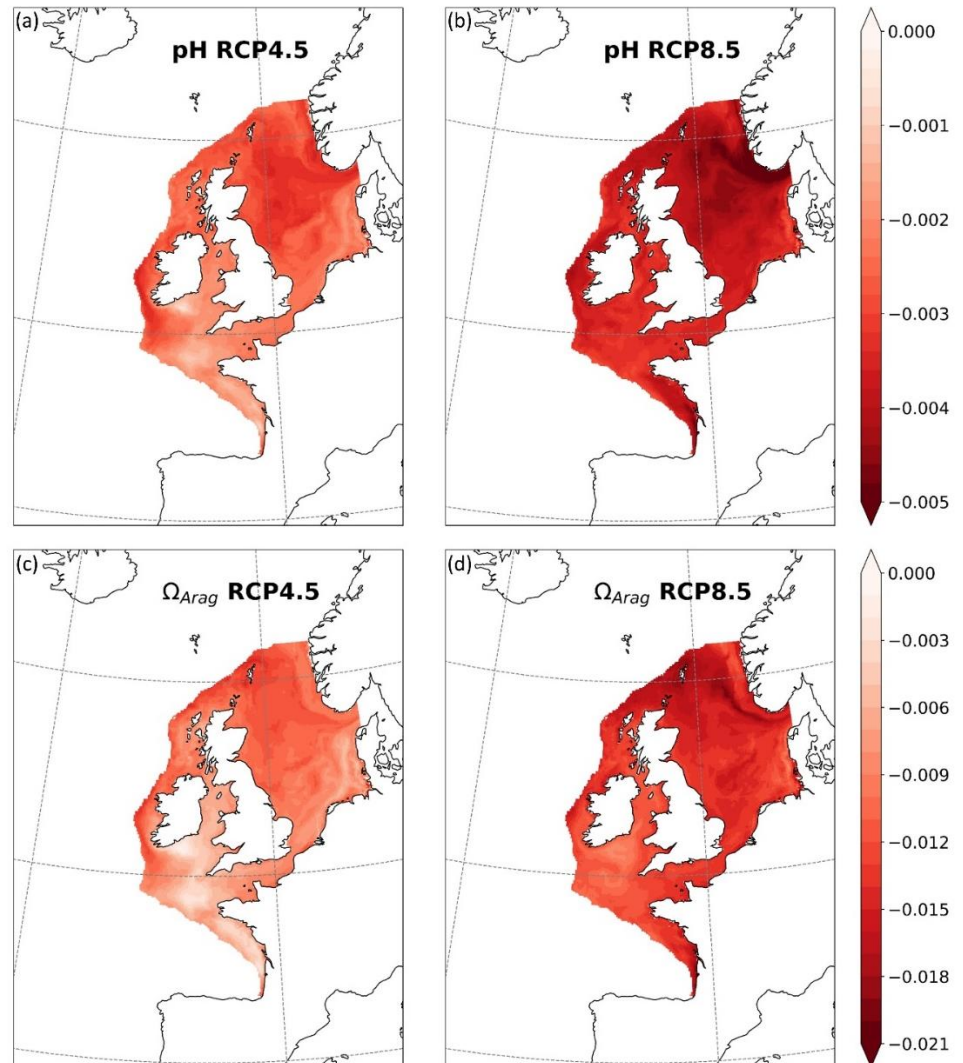


Figure 9: The trend of bottom water pH (top;  $\text{yr}^{-1}$ ) and  $\Omega_{Arag}$  (bottom;  $\text{yr}^{-1}$ ) between 2015 and 2049 as projected by the AMM7-NEMO-ERSEM model under the RCP4.5 scenario (left) and RCP8.5 scenario (right) on the north-western shelf. Only data within the OSPAR regions II, II and IV has been shown. (OSPAR, 2022)

As a result of the seasonal signal in carbonate chemistry, the first episodic undersaturation events (in relation to aragonite) are projected to begin by year 2030, and to then become a recurrent, but spatially restricted, feature from the middle of this century. Aragonite undersaturation is projected to increase significantly after 2070 to become a widespread phenomenon by the end of the century under RCP8.5 scenarios, when >30% of the North-West European Shelf seas may experience undersaturation for at least one month of each year (Figure 10).

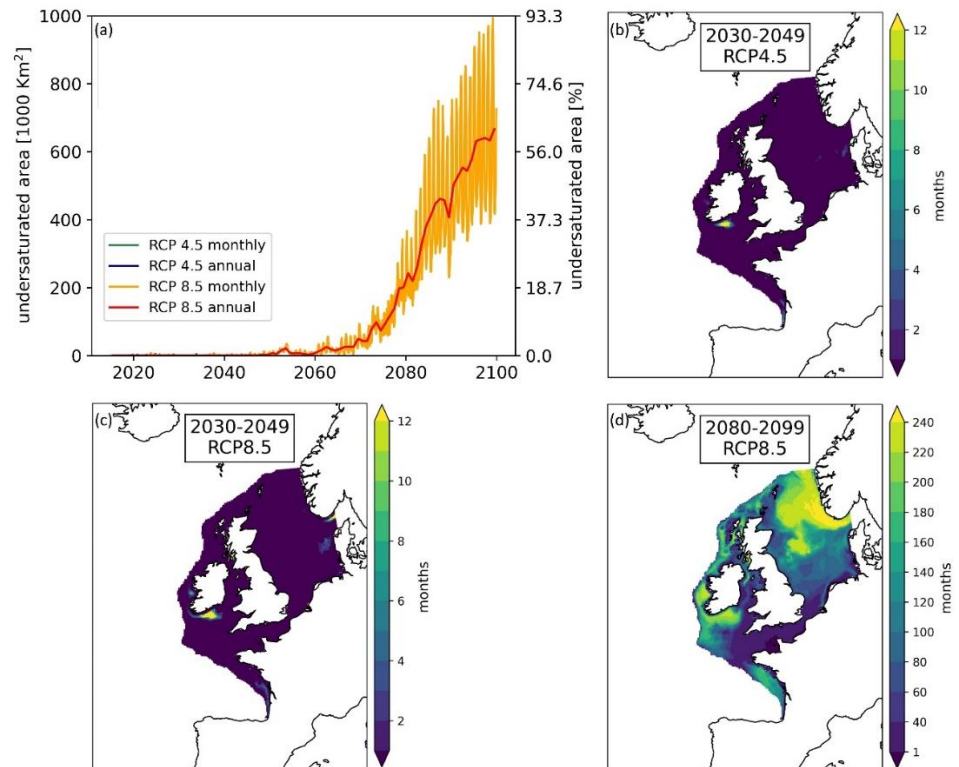


Figure 10: (a) Projection of the extent of aragonite undersaturation ( $\Omega_{Arag} < 1$ ) in bottom water on the shelf from 2015 to 2099 (monthly and annual means). Note that data for RCP4.5 only extends until 2050 and they are all very low, close to the bottom axis. (b – d) Areas (and frequency) where aragonite undersaturation ( $\Omega_{Arag} < 1$ ) will occur in bottom water on the shelf by mid-century (b and c) and by the end of the century (d). (b) shows the areas where undersaturation occurs in scenario RCP4.5 and its frequency in the period from 2030 to 2049. The dark blue colour shows areas where undersaturation never occurs, the yellow colour highlights areas where undersaturation occurs more frequently (at most a month per year on average). (c and d) show the same for the scenario RCP8.5 for the mid-century (c) and the end of the century (d). Note that (d) has a different colour range: here a yellow colour means that undersaturation is a constant feature in those 20 years. No simulation was available for the end of the century for scenario RCP4.5 (OSPAR, 2022).

### Biological impacts

Most future projections of impacts on organisms and ecosystems come from laboratory work and from investigating environments that are analogues for future conditions, such as CO<sub>2</sub> vents (e.g. Agostini *et al.*, 2018). As highlighted in the introduction, these impacts and knock-on repercussions can be diverse and the risk to ecosystems will depend on a combination of organisms' sensitivity to ocean acidification (and other stressors) and how exposed it is to conditions that are outside the range that it has historically been exposed to, together with the rate of change in conditions. Long-lived species, as well as early life stages, are believed to be most at risk due to their low ability to adapt (in the case of long-lived species) or their lack of physiological capability to respond to change (in the case of early life stages).

Cold-water corals, such as *Lophelia pertusa*, are calcifying habitat-forming organisms. Approximately 90% of currently known reef-forming cold-water corals are distributed in waters saturated with aragonite (Davies and Guinotte, 2011), but there are also natural populations of *L. pertusa* that occur in



aragonite undersaturated waters (Davies and Guinotte, 2011; Baco *et al.*, 2017), demonstrating that live cold-water corals are capable of persisting in corrosive waters. As a calcifying organism, *L. pertusa* is expected to be particularly vulnerable to ocean acidification. For example, by 2060, around 85% of known deep-sea cold-water coral reefs in the UK could be exposed to waters that are corrosive to them (Jackson *et al.*, 2014). Other threatened and declining species and habitats, especially calcifying species and their habitats, such as oyster (*Ostrea edulis*), mussel (*Mytilus edulis*) and horse mussel (*Modiolus modiolus*) beds, and maerl beds (coralline red algae *Corallinaceae*) are also at risk from ocean acidification (OSPAR, 2022). Studies from the Mediterranean, and other coastal regions, show that ocean acidification (at levels that would occur at global warming of 4°C, scenario A1B) may alter the structure of critical benthic habitats, for example by causing an increase in fleshy algae, macroalgae and seagrasses, which could then compete against coralline algae (Zunino *et al.*, 2017). The complex interactions between autotrophs, habitat-forming species and biodiversity is yet to be fully understood. Initial work suggests that high biodiversity can ameliorate some of the more negative impacts of sensitive species (Rastelli *et al.*, 2020), but further work on ecosystem level interactions as well as impacts on biogeochemical functioning need to be taken into consideration. Further detailed assessment of the impacts of ocean acidification are considered under the MCCIP impacts reviews.

The high levels of variability within the nearshore, highlighted from the observational and modelling data, need to be taken into account when considering an organism's or ecosystem's response to ocean acidification. Organisms living within this high variability may already have mechanisms that allow them to cope and survive, and therefore be less susceptible to future ocean acidification. At the same time, higher variability might lead to higher likelihood of passing critical thresholds even if for short periods, which could impose greater risk of acute effect on organisms. Indeed, the projected expansion of undersaturated waters does not imply the collapse of all calcifying species, as it represents a chemical threshold and not necessarily a biological one; but it highlights a further threat that they will be exposed to. Finally, ocean acidification is not occurring in isolation, most impacts on species will manifest through the multi-stressor impact of climate change, acidification and other anthropogenically-induced pressures.

## CONFIDENCE ASSESSMENT

### *What is already happening?*

Level of agreement or consensus (inc. dataset agreement and model confidence)	H		(x)	X
	M			(x)
	L			
		L	M	H

Amount of evidence (theory / observations / models)

As shown in the above schematic, it is not easy to give a single confidence value to ‘what is already happening’, since different considerations apply to the different aspects discussed in this review. It is more meaningful for a ‘confidence’ rating to be expressed in relation to a specific statement (e.g. as used by IPCC), than for a relatively wide topic area. The fundamental chemistry underlying air–sea CO<sub>2</sub> exchange and the pH decline that results from anthropogenic CO<sub>2</sub> uptake is very well established (high evidence, high agreement). In open ocean regions, the change in chemistry is observable, having been investigated by a multitude of independent techniques (observations, modelling and reanalysis assessments) with concordant results (medium evidence, high agreement).

There are still significant knowledge gaps for shelf-sea carbonate chemistry, including many of the factors affecting local and short-term variability. As highlighted here, the models do not generally capture the short-term and local variability of the carbonate system, which is where much of the interest is in terms of ecosystem services for humans living in the coastal zone. There is therefore a split in confidence: first, there is medium level (but growing) evidence from observations, with high agreement that ocean acidification is occurring in the UK shelf seas; and second, there is high evidence from theory of the carbonate system in these shelf regions, but medium level of agreement between models and data.

### What could happen in the future?

Level of agreement or consensus (inc. dataset agreement and model confidence)	H			
	M		X	(X)
	L			
		L	M	H

Amount of evidence (theory / observations / models)

As above, it is not easy to give a single confidence value to ‘what could happen in the future’: different considerations apply to different aspects, and there are additional inherent uncertainties relating to societal behaviour. In particular, whether commitments made to reduce greenhouse gas emissions under the Paris Agreement will be implemented. Reports after the UNFCCC COP26 in November 2021 suggest that Nationally Determined Contributions (NDCs) are still under committed for achieving a 1.5°C target. If there is full implementation of all announced targets including net zero targets, Long Term Strategies (LTS) and NDCs occurs, then optimistically global temperatures may be limited to between 1.5 – 2.4 °C (Climate Action Tracker).

There is very high confidence in the first order expectation that global mean seawater pH and saturation states of carbonate minerals will decrease in response to increasing atmospheric CO<sub>2</sub>. However, specific details of regionally resolved decadal trends and changes in interannual and seasonal variability are less certain, because they are emergent properties of a complex, interactive array of drivers. The high importance of relatively small-scale processes in near-coastal environments adds uncertainty to model results for these regions. These uncertainties are gradually being reduced by improving the spatial and temporal resolution at which simulations are carried out, as well as further developing the representations of biogeochemical processes that are employed within the models. This uncertainty, together with the uncertainty about which future scenario might prevail, and the lack of regional assessment using the lower RCP2.6 scenario, means the overall confidence level is at ‘medium’ for understanding of the future of ocean acidification and its impacts in UK Shelf seas.

## KEY CHALLENGES AND EMERGING ISSUES

1. Lack of data prevents good understanding of near-shore dynamics and trends as well as being able to relate physicochemical changes to biological change. To aid this there is a need to:
  - Increase near-shore and shallow coastal environments monitoring activities, helping to identify and track higher spatial and temporal resolution when compared with open ocean to understand the drivers (e.g. physico-chemical, biological, etc.) occurring alongside the anthropogenic increase in CO<sub>2</sub>, and to project biological response.
  - Sustain long-term time-series observations of the marine carbonate system at key point sites and transects with biological monitoring to ascertain the scale and magnitude of these observed changes.
  - Increase coupling of physicochemical and biological monitoring to support the assessment of ecosystem risk and consequences, and better inform planning and management strategies.
  - Develop accurate and stable autonomous observing technologies for pH and related variables, deploying them in difficult-to-sample regions, and linking and analysing their measurements effectively with other data streams.
2. Ocean acidification effects will not act in isolation; future ocean acidification studies need to be conducted in relation to other stressors (e.g. temperature, oxygen, metals, etc.). This requires:
  - Local ecosystem and societally relevant experimental work together with improves ability to assess changes in multiple parameters in the field.
  - Improved spatial and temporal resolution of models, along with their descriptions of biogeochemical processes, to capture the relatively small-scale controls on the marine carbonate system in complex coastal and shelf sea environments.
3. Data is not always readily available or compatible to bring together in the wholistic way needed to make these large-scale assessments of the trends and impacts of ocean acidification. Activity in capacity building is needed including:
  - Co-ordinating intercomparison and intra-calibration activities as well as capacity development of quality control schemes to support and increase training and proficiency of carbonate chemistry and biological monitoring across UK laboratories.
  - Continued support a centralised Data Hub: a repository for cataloguing time-series records and storage of metadata across UK sites, which shares the vocabulary and metadata standard of the wider OA community thus allowing data harvesting and

sharing between data archiving centres and data product generators (e.g. IOC, SOCAT, GLODAP).

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