Ocean Acidification around the UK and Ireland

Findlay, H.S.[1], Artioli, Y.[1], Greenwood, N.[2], Hartman, S.[3], Flohr, A.[3], León, P.[4], Stiasny, M.[5], and Cronin, M.[6]

[1] *Plymouth Marine Laboratory, West Hoe, Plymouth, PL1 3DH, UK.*

[2] *The Centre for Environment, Fisheries and Aquaculture (Cefas), Lowestoft Laboratory, Pakefield Road, Lowestoft, Suffolk, NR 33 0HT, UK.*

[3]*National Oceanography Centre Southampton, European Way, Southampton, SO14 3ZH, UK.*

[4] *Scottish Government's Marine Directorate, Marine Laboratory, 375 Victoria Road, Aberdeen, AB11 9DB, UK.*

[5]*University of Southampton, School of Ocean and Earth Science, University Road, Southampton, SO17 1BJ, UK.*

[6]*Marine Institute, Rinville, Oranmore, Galway, H91 R673, Ireland*

KEY FACTS

What is already happening

- Atmospheric CO_2 exceeded 420 ppm in 2024 and has continued to increase by approximately 2.5 ppm per year over the last decade. The global ocean absorbs approximately a quarter of anthropogenic carbon dioxide (CO_2) emissions annually.
- The North Atlantic Ocean contains more anthropogenic CO_2 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.

Citation: Findlay, H.S., Artoli, Y., Greenwood, N., Hartman, S., Flohr, A., León, P., Stiasny, M. and Cronin, M. Ocean acidification around the UK and Ireland. MCCIP Science Review 2025, 31pp.

doi: 10.14465/2025.reu03.oac

Submitted: 11 2024

Published online: 02 2025

- High levels of nearshore variability in carbonate chemistry may mean that some coastal species have a higher adaptative capacity than others. However, all species are at increased risk from extreme exposure episodes.

SUPPORTING EVIDENCE

Introduction

CO_2 uptake and acidification

The average atmospheric carbon dioxide (CO_2) concentration exceeded 420 parts per million (ppm) in 2024, a 52 % increase above pre-industrial levels, and increasing on average by 2.5 ppm per year over the past decade (Friedlingstein et al., 2024). This ongoing increase is primarily due to CO_2 release by fossil fuel combustion, cement production and land-use change (mainly deforestation) (Friedlingstein et al., 2024; IPCC, 2021). Over a quarter of this annual anthropogenic CO_2 emission dissolves into the Earth's oceans each year (fossil fuel CO_2 emissions = 10.1 ± 0.5 gigatonnes of carbon per year (Gt C yr^{-1}, 1 Gt = one thousand million tonnes)), Land-use change emissions = 1.0 ± 0.7 Gt C yr^{-1}, ocean uptake = 2.9 ± 0.4 Gt C yr^{-1}; (Friedlingstein et al., 2024). Once dissolved, the CO_2 no longer influences the atmospheric heat budget, so this oceanic uptake mitigates human-driven warming and climate change. However, dissolved (or aqueous) CO_2 undergoes a chemical reaction that releases hydrogen ions (H+), thereby decreasing the seawater's pH (Figure 1). As pH declines, the carbonate ion concentration ($[CO_3^{2-}]$ also declines (Figure 1). The $[CO_3^{2-}]$ controls the saturation state (Ω) of calcium carbonate ($CaCO_3$) minerals such as aragonite (Ω_{Arag}) and calcite (Ω_{Cal}) and indicates the ability of these minerals to precipitate (form) or dissolve. At Ω >1 water is supersaturated with Ca^{2+} and CO_3^{2-} ions allowing $CaCO_3$ minerals to form. When Ω <1, seawater is undersaturated with Ca^{2+} and CO_3^{2-} ions and therefore any exposed $CaCO_3$ minerals are prone to dissolution. These collective changes in marine carbonate chemistry are known as 'ocean acidification'.

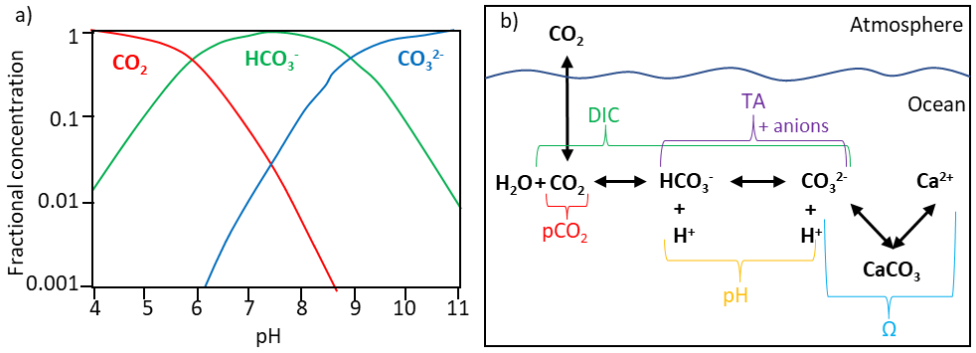


Figure 1: (a) Relationship between seawater pH and the relative concentrations of the constituents that make up total Dissolved Inorganic Carbon (DIC). These constituents are: aqueous CO_2, bicarbonate ions (HCO_3^-) and carbonate ions (CO_3^{2-}). At typical seawater pH, a little over 8, about 90% of DIC is in the HCO_3^- form, about 10% is CO_3^{2-}, and <1% is aqueous CO_2. Adding more CO_2 increases its

relative concentration, shifting the system to lower pH, and thus decreases the abundance of CO_3^{2-}. (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_2 (pCO_2), 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 0.0017 y^{-1} (E.U. Copernicus Marine Service Information, DOI (product): https://doi.org/10.48670/moi-00224), such that in year 2020 the surface ocean was approximately 40 % more acidic than pre-industrial levels. Trends for increasing seawater CO_2 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 (Ma et al., 2023; Schlunegger et al., 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 within 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_2 of the surrounding seawater or indirectly through changes to food webs and processes (Birchenough et al., 2015). 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_2 (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_2 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 $CaCO_3$ 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 $CaCO_3$ 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 for 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_2 have been shown to impact numerous process including carbon cycling and uptake, metal speciation (Breitbarth et al., 2010; Zhu et al., 2021), nutrient cycling (e.g. Wannicke et al., 2018), and production of climatically-important gases (e.g. Campen et al., 2022; Hopkins et al., 2020).

WHAT IS ALREADY HAPPENING?

Open ocean – wider Atlantic region/deep waters

Regardless of where it is emitted, anthropogenic CO_2 is mixed throughout the Earth's atmosphere by wind and weather. The increasing amount of CO_2 taken up by the oceans and corresponding pH decline are therefore global phenomena (McKinley et al., 2017). By using a novel combination of machine learning-based methods and target transformations, (Gregor et al., 2024) were able to globally estimate surface ocean fCO_2 and the associated sea-air CO_2 fluxes on a resolution of 8-day by 0.25° × 0.25° over the period 1982 to 2022. This OceanSODA-ETHZv2 product implies a total oceanic sink for anthropogenic CO_2 of 2.33 Gt C yr^{-1} for 1990–1999, 2.52 Gt C yr^{-1} for 2000–2009, and 2.85 Gt C yr^{-1} for 2010–2019 (Gregor et al., 2024). The latter value corresponds well with the average ocean uptake calculated for the global carbon budget, of 2.9 ± 0.4 Gt C yr^{-1} over the past decade (Friedlingstein et al., 2024) However, new work in the Atlantic region, on near surface temperatures and their impact on CO_2 flux, suggests a 0.18 PgC yr^{-1} bias due to previously neglecting natural vertical temperature gradients; equivalent to a 6% underestimation of the global ocean sink (based upon a global sink of 2.9 PgC yr^{-1}) (Ford et al., 2024). 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_2 uptake (Landschützer et al., 2016).

The magnitude of the seasonal cycle of sea surface fCO_2 has also increased between the 1980s and present day, driven by stronger seasonal cycles in fCO_2 drivers (e.g. temperature), augmented by the lower chemical buffer capacity of seawater at higher fCO_2 due to ocean acidification (Landschützer et al., 2018; Watson et al., 2020). 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_2 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_2 did not increase between the period 2002 to 2016, there was an increase in the seasonality (i.e. the difference in fCO_2 between winter and summer) over time, demonstrating that the region has continued to absorb atmospheric CO_2 in recent years, and that this CO_2 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: A recent update on the pH trend at the ESTOC site in the North Atlantic shows ocean pH is declining at a rate of 0.002 ± 0.0001 yr−1 in the upper 100 m. This rate is 20% higher than values determined for the period 1995–2010. The observations show that the trends of the carbonate variables along the water column in the eastern subtropical ESTOC region are dominated by anthropogenically induced changes, observed in the whole water profile (González-Dávila and Santana-Casiano, 2023). Data from 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). Calculation of pH (from annual DIC and TA samples) at the PAP-SO suggests an annual surface pH decrease of -0.004 ± 0.03 pH between 2020 and 2024, compared with -0.02 ± 0.014 from direct pH sample measurements at the site. These are based on discrete sampling carried out once a year at PAP-SO during the productive season. A range of EOVs are measured directly by autonomous sensors deployed at the PAP-SO, and to improve temporal resolution Lab on chip pH measurements will be incorporated from 2025 for year-round direct pH measurements measured spectrophotometrically (Yin et al., 2021).

Data from the autumn (southbound) AMT cruises suggests the whole Atlantic has seen a decrease in ocean pH (mean -0.0013 ± 0.0009 yr^{-1}) with some areas in the North East Atlantic (>40 N) observing pH rates faster than -0.002 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 pH unit yr^{-1} and a decline in Ω_{Arag} of -0.006 to –0.012 yr^{-1} (Olafsson et al., 2009), while data from the open ocean sub-Arctic region shows surface pH declines of -0.0033 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 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 CO_2 from the atmosphere (Fransner et al., 2022; Skjelvan 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 CO_2 than any other ocean basin, due to deep-water formation that occurs there, which effectively transfers CO_2 from the surface into the ocean interior (Khatiwala et al., 2013; Sabine et al., 2004). While North Atlantic deep-water formation is climatically beneficial in terms of

exporting 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 (McGovern et al., 2023). In the Irminger Sea and Iceland Sea there is particular rapid acidification in the interior ocean, and this has been previously highlighted (García-Ibáñez et al., 2016; Olafsson et al., 2009; Pérez et al., 2021, 2018; Vázquez-Rodríguez et al., 2012). Latest observations have shown that during the 2010s, the subpolar North Atlantic experienced a 50%–86% increase in anthropogenic CO_2, which contributed to acidification in upper ocean layers by 53%–68% and >82% in the interior ocean (with acidification trends between -0.0006 and -0.0032 units yr^{-1}, (Curbelo-Hernández et al., 2024) 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 fCO_2 taken from observations around the North-West European Shelf (NWES) seas have shown that variability increases from about 100 µatm in locations sampled further than 300 km offshore, to >300 µatm within about 10 km of land (Figure 2). There is also a strong seasonal signal in fCO_2 observable in the Celtic Sea, Irish Sea and northern North Sea (Figure 3). During the spring and summer months biological activity (photosynthesis) captures CO_2 in the stratified surface layer, which then gets transported into deeper waters. During autumn and

winter, the stratification breaks down, and CO_2 that has been produced at depth through respiration and remineralisation is mixed throughout the water column causing a peak in fCO_2 during winter. There are exceptions, for example in the southern bight of the North Sea and eastern English Channel thermally-driven increases in fCO_2 occur in summer (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 fCO_2 during periods of greatest river flow (Figure 3). As CO_2 is a major driver for pH change and ocean acidification, the dynamics of the pH correspond to fCO_2, such that when 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).

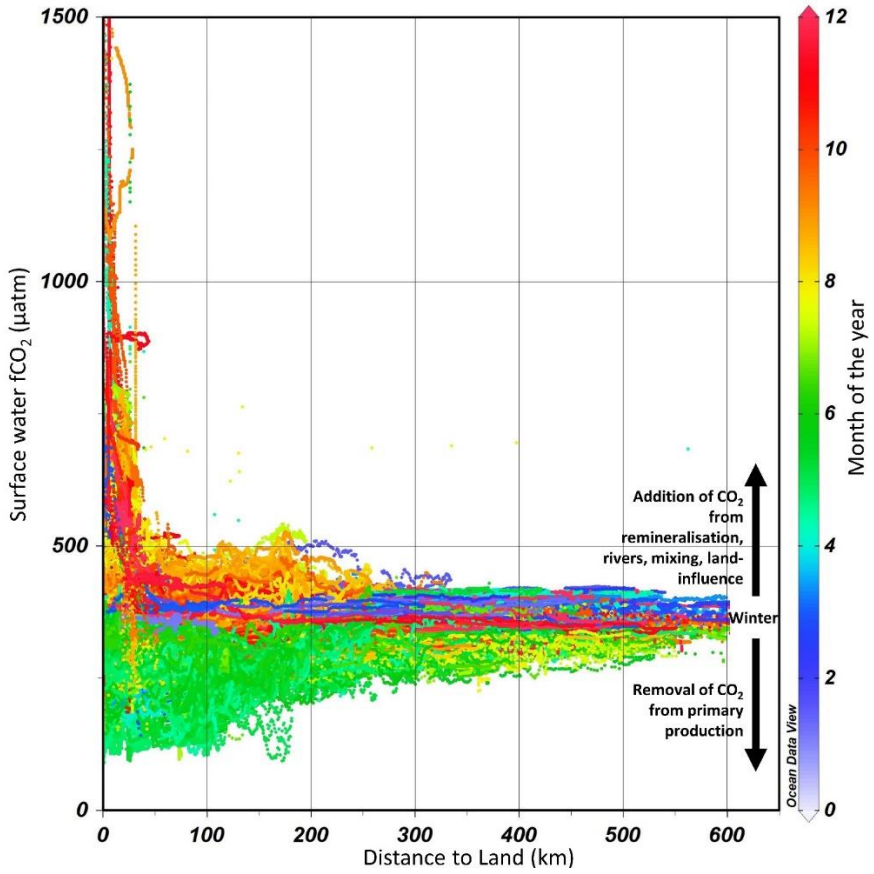


Figure 2: fCO_2 from SOCATv.2021 for North-West European Shelf Sea region (see map of data points in Figure 3) in relation to distance to land (km). Colour bar represents the continuous time with respect to month of the year. Data are from year 2010 to 2020. Arrows illustrate the processes that increase or decrease CO_2 from the winter value.

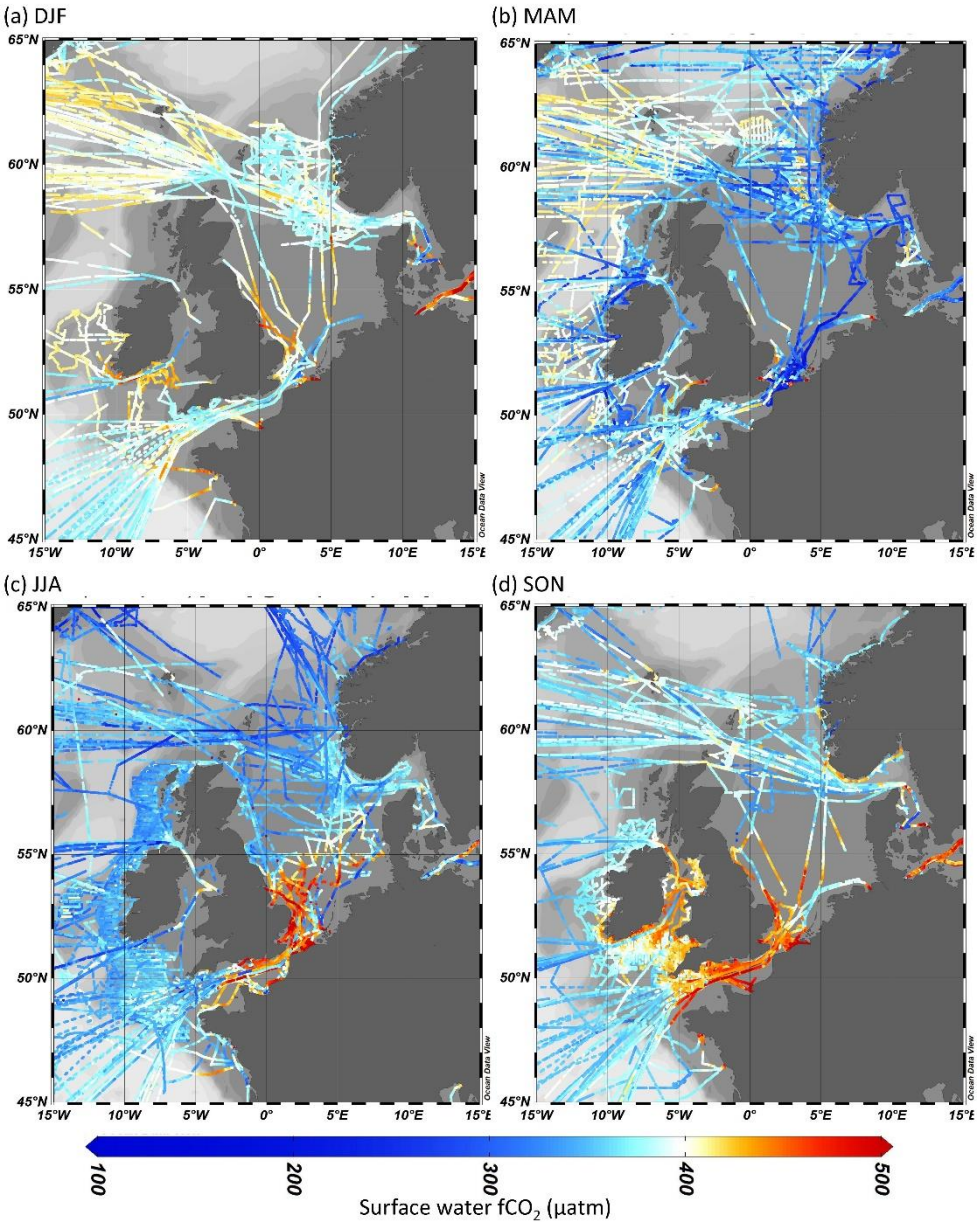


Figure 3: Surface water fCO_2 between years 2010 and 2023 from SOCATv2024 for the North-West European Shelf Seas separated by season (a) winter – December, January, February (DJF); (b) Spring – March, April, May (MAM); (c) Summer – June, July, August (JJA); (d) Autumn – September, October, November (SON).

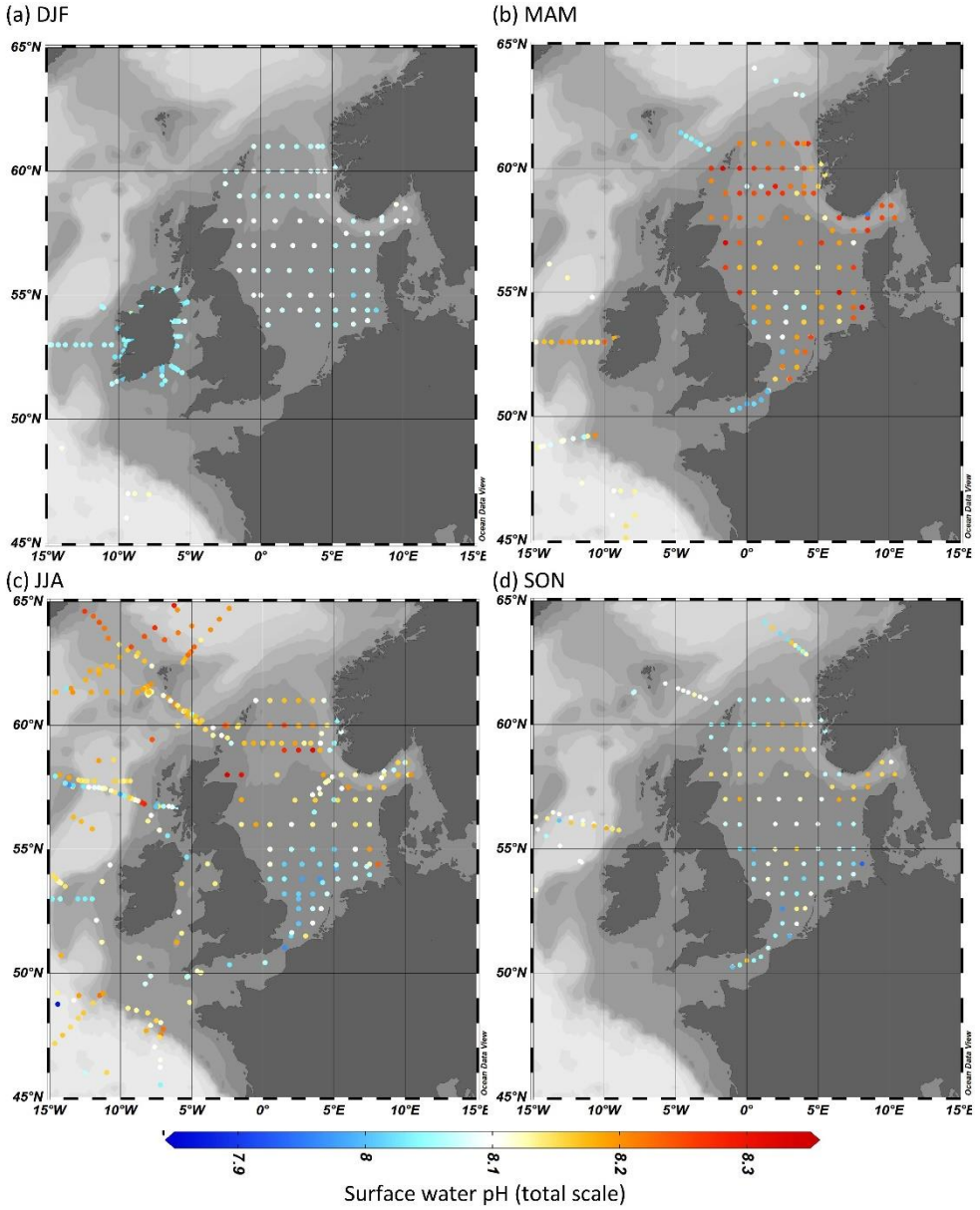


Figure 4: Surface water pH between years 1981 and 2021 from GLODAPv2.2023 for the North-West European Shelf Seas separated by season (a) winter – December, January, February (DJF); (b) Spring – March, April, May (MAM); (c) Summer – June, July, August (JJA); (d) Autumn – September, October, November (SON).

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, the

average trend of surface water pH over the entire domain is -0.0020±0.0002 pH units yr^{-1}, with some spatial variation (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 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 (McGovern et al., 2023).

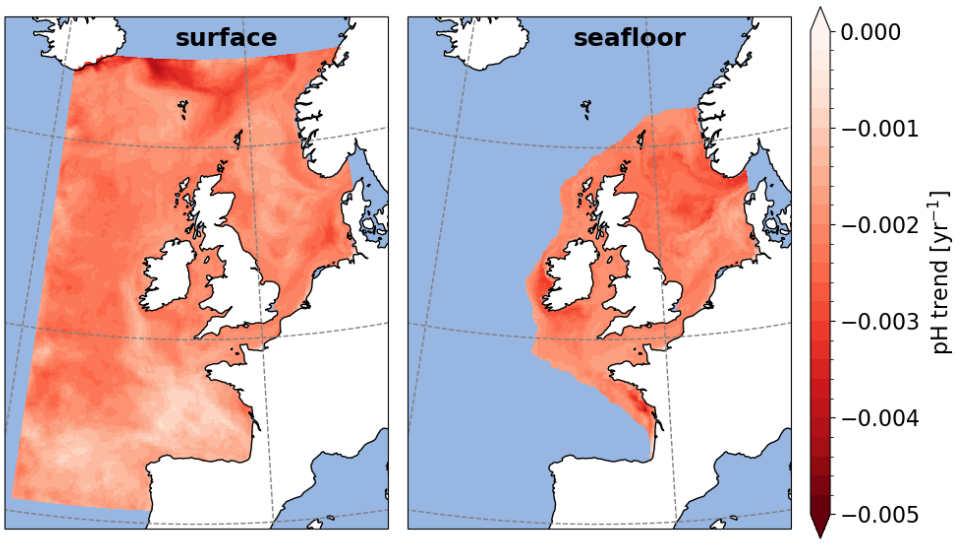


Figure 5: NEMO-ERSEM Model hindcast pH trend projections for the period 1990-2015 for surface waters (left) and waters above the seafloor (right). Blue areas fall outside of the model domain or are seafloor area deeper than 200m, where the model reliability significantly decreases.

In looking at alternative products to the DARE_UK modelling, the Copernicus (CMEMS) Atlantic -European North West Shelf- Ocean Biogeochemistry Reanalysis product (https://doi.org/10.48670/moi-00058) was investigated. However it became apparent there are uncertainties on the simulated trend of pH arising from the boundary condition set-up, which prevented the data from being used in this report. In particular, the boundary conditions for DIC and TA have been set using the GLODAPv2 climatology, and therefore it does not include the impact of the increasing trend of DIC in the Atlantic Ocean outside of the model domain. This leads to an underestimation of the OA trends in the off-shelf area, especially in the North East section between Iceland and the shelf, where the influence of both the Western and the Northern boundary is stronger.

A new modelling study has highlighted that in the NWES, the efficiency of oceanic CO_2-uptake, and hence fCO_2 as well as acidification, strongly depends on the biological uptake of inorganic carbon along with carbon export, which are both influenced by organic matter stoichiometry (Demir et al., 2024). Including variably stoichiometry (as compared to fixed Redifeld

stoichiometry), resulted in an increase of the annual net CO_2 -uptake in the NWES by 10-33% (Demir et al., 2024).

Near-shore coasts – long-term stations around the UK and Ireland

As is highlighted by the SOCAT fCO_2 data, the nearshore/ coasts 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 (higher frequency, i.e. weekly) carbon time–series recorders in the UK are the Scottish Government's Marine Directorate (SG MD)'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; McEvoy et al., (2023)). The carbonate system parameters have been measured weekly (conditions permitting) since the end of 2008 at both these sites (noting that there are data gaps at Stonehaven between 2014 and 2017). Since 2018, carbonate chemistry monitoring was established by SG MD at the monitoring site in Loch Ewe, which is situated in 40 m water depth in the outer basin of the loch in north-west Scotland (map in Figure 6). The Irish Marine Institute also began monitoring the carbonate system at the Mace Head coastal observatory in 2018. This is situated on the Atlantic-facing Irish west coast, in approximately 20 m water depth, about 2 km west of Mace Head, where the University of Galway's Mace Head Global Atmosphere Watch station is located. Multiple sensors, including pCO_2 and pH, are deployed and this is supported by periodic water sampling for additional physico-chemical and biological parameters. The Western Channel Observatory open shelf station E1, located 46 km offshore (map in Figure 6), also has carbonate chemistry time-series from 2018 to present, but samples are taken less frequently (monthly).

The UK stations show seasonal dynamics in the carbonate system driven by a combination of temperature and biological activity (higher [lower] autumn/winter fCO_2 [pH] and lower [higher] spring/summer fCO_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., 2021). Despite this weekly, seasonal, and annual variability, significant trends of increasing fCO_2 and decreasing pH have been found in surface water of the datasets (Figure 7). The WCO L4 time-series records show an increase in fCO_2 of 14.1 ± 126 µatm yr^{-1} (r^2 = 0.171, n = 408, p <0.0001) and a decrease in pH of -0.0115 ± 0.0939 yr^{-1} (r^2 = 0.201, n = 489, p <0.0001) between 2008 and 2023 The Stonehaven time–series also show very high variability and fast rates of fCO_2 increase and pH decrease (18.3 ± 120 µatm yr^{-1} (r^2 = 0.308, n = 279, p <0.0001) and -0.0145 ± 0.0764 yr^{-1} (r^2 = 0.407, n = 277, p <0.0001), respectively over the same period; Figure 7). Noting there is increased

uncertainty in the Stonehaven data for the period 2017 – 2023 (± 0.104) compared to the period 2008 - 2013 (± 0.0467). These rates are also seen at WCO station E1 in the monthly records (pH trend of -0.0150 ± 0.0975 yr^{-1} and fCO_2 trend of 20.7 ± 154 µatm yr^{-1} between 2008 and end of 2022) and are statistically insignificant to WCO L4 trends given the large variability. 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 yr^{-1} in some of these regions (McGovern et al., 2023). Loch Ewe and Mace Head time-series are not yet long enough to provide sufficient trend analysis, but initial results show CO_2 is increasing and pH decline (Figure 8).

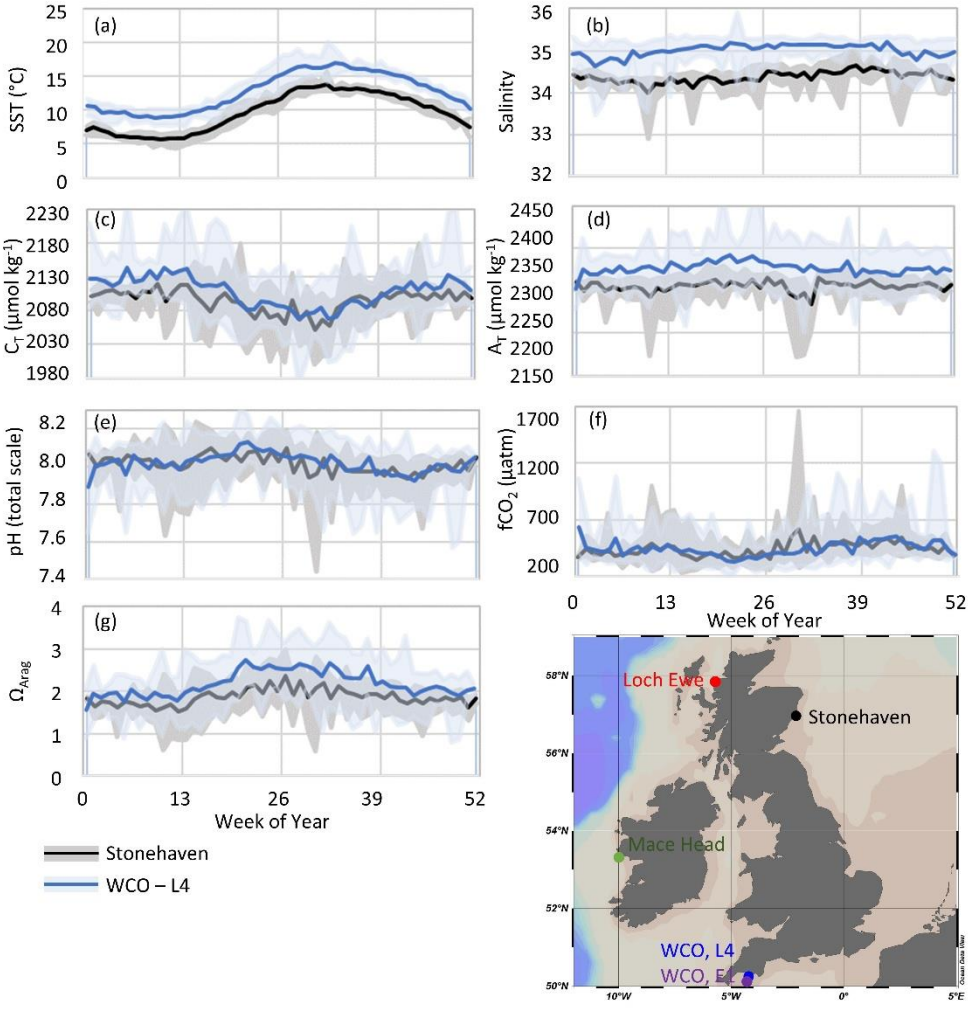


Figure 6: Seasonal cycle at stations Stonehaven (black and grey lines) and WCO L4 (blue lines) for surface water (a) temperature (SST), (b) salinity, (c) dissolved inorganic carbon (CT), (d) total alkalinity (AT), (e) calculated pH, (f) calculated fCO_2, (g) calculated aragonite saturation state. Thick lines are mean values, thin lines represent maximum and minimum values, data are from full time–series periods (2008 – 2023 Stonehaven; 2008 – 2023 WCO L4). Map inset shows the stations Stonehaven and WCO L4, but also the location of WCO E1, Loch Ewe and Mace Head.

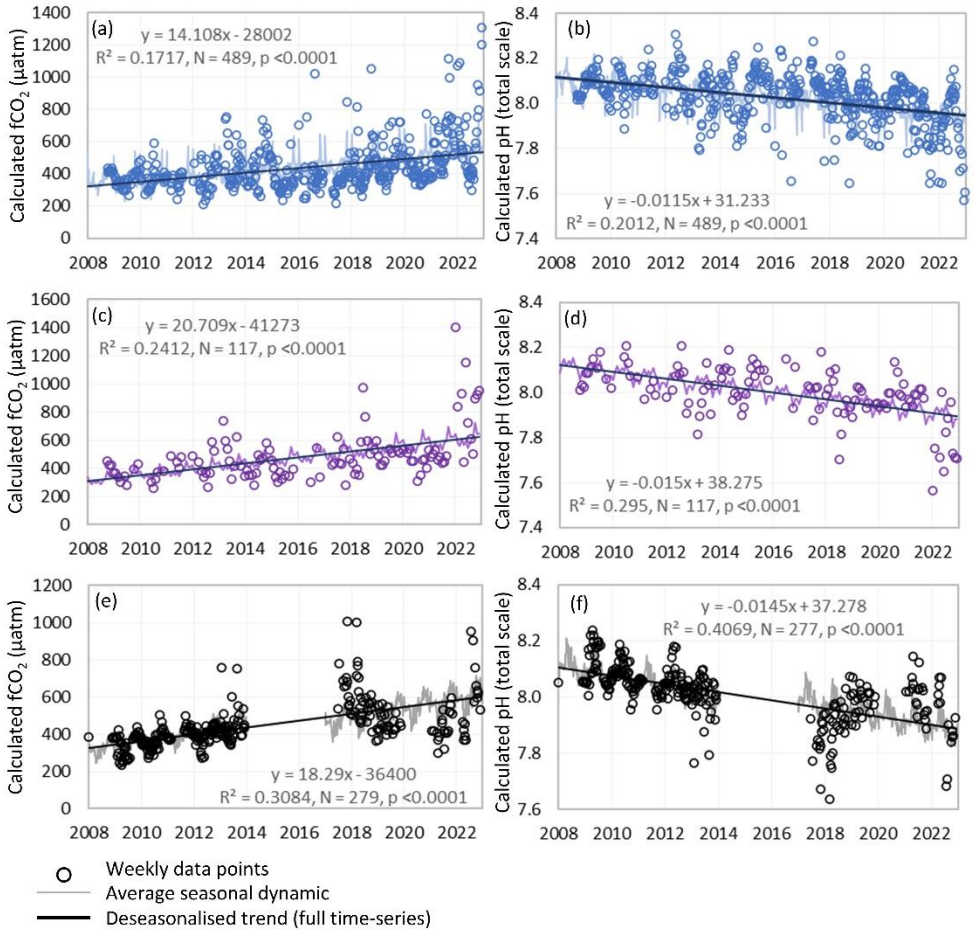


Figure 7: Time–series data (open circles) for WCO L4 (a and b), WCO E1 (c and d) and Stonehaven (e and f) showing surface water fCO_2 (a, c and e) and pH (b, d and f). Both values are calculated from measured dissolved inorganic carbon and total alkalinity. The average seasonal fit is shown as the thin line; deseasonalised trends for each full time–series are shown as thick lines. Note the y-axis scales differ between subplots.

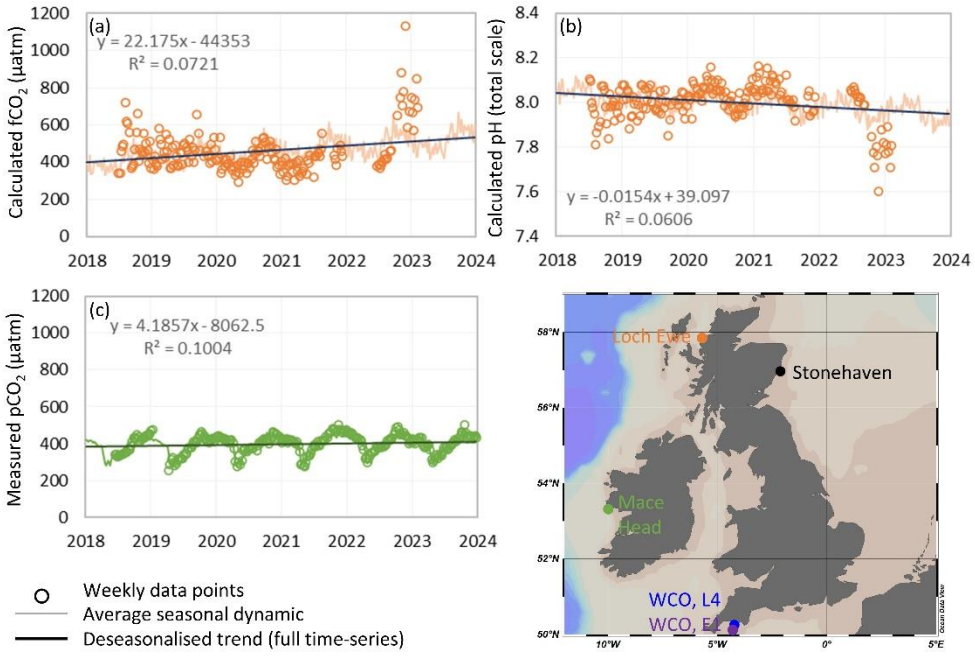


Figure 8: As with Figure 7 but for time-series stations Loch Ewe (a and b) and Mace Head (c).

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 Ω_{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 Ω_{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 (McGovern et al., 2023). 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 Ω_{Arag}, rather than only absolute thresholds (León et al., 2020), might affect the shell integrity of plankton calcifiers. Although other factors affecting the community response need to be analysed further, 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 (McGovern et al., 2023), 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 yr^{-1} under RCP4.5 and -0.003 yr^{-1} under RCP8.5 from year 2015 until 2050 (Figure 9). Significant spatial variability in the rate of pH decline is projected, with changes as fast as -0.005 yr^{-1} (RCP8.5) in some coastal areas like the Bristol Channel and the West coast of Denmark, and as slow as -0.002 yr^{-1} (RCP8.5) in the Celtic Sea (McGovern et al., 2023). The projected spatial patterns of surface $CaCO_3$ mineral saturation state matches that for pH (Figure 9). 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 (McGovern et al., 2023).

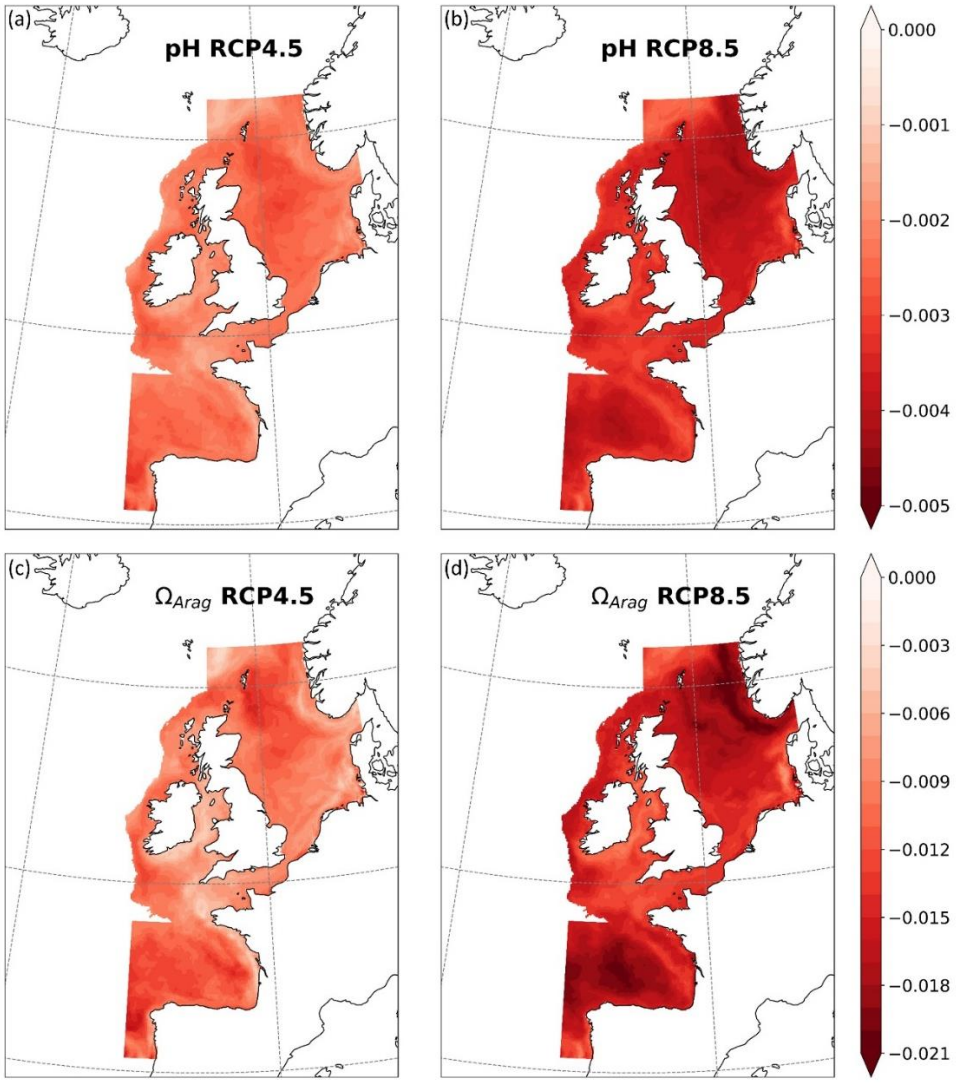


Figure9: Trend of surface pH (top; yr-1) and Ω_{Arag} (bottom; yr-1) between 2050 and 2015 as projected by the AMM7-NEMO-ERSEM model under the RCP 4.5 scenario (left) and RCP8.5 scenario (right). Only data within the OSPAR regions II, II and IV has been shown. (McGovern et al., 2023)

On the shelf (water depth <200 m), the bottom waters around the UK and Ireland are projected to experience faster rates of decline in pH and Ω_{Arag} 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^{-1} (RCP4.5) and -0.0040 yr^{-1} (RCP8.5) between 10 % and 15% more rapid than at surface (Figure 10). 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_{Arag} are between -0.0100 yr^{-1} (RCP4.5) and -0.0145 yr^{-1} (RCP8.5) and the spatial pattern is similar to the one of pH, with Ω_{Arag} decline being more rapid in the Northern North Sea and close to the shelf break (McGovern et al., 2023).

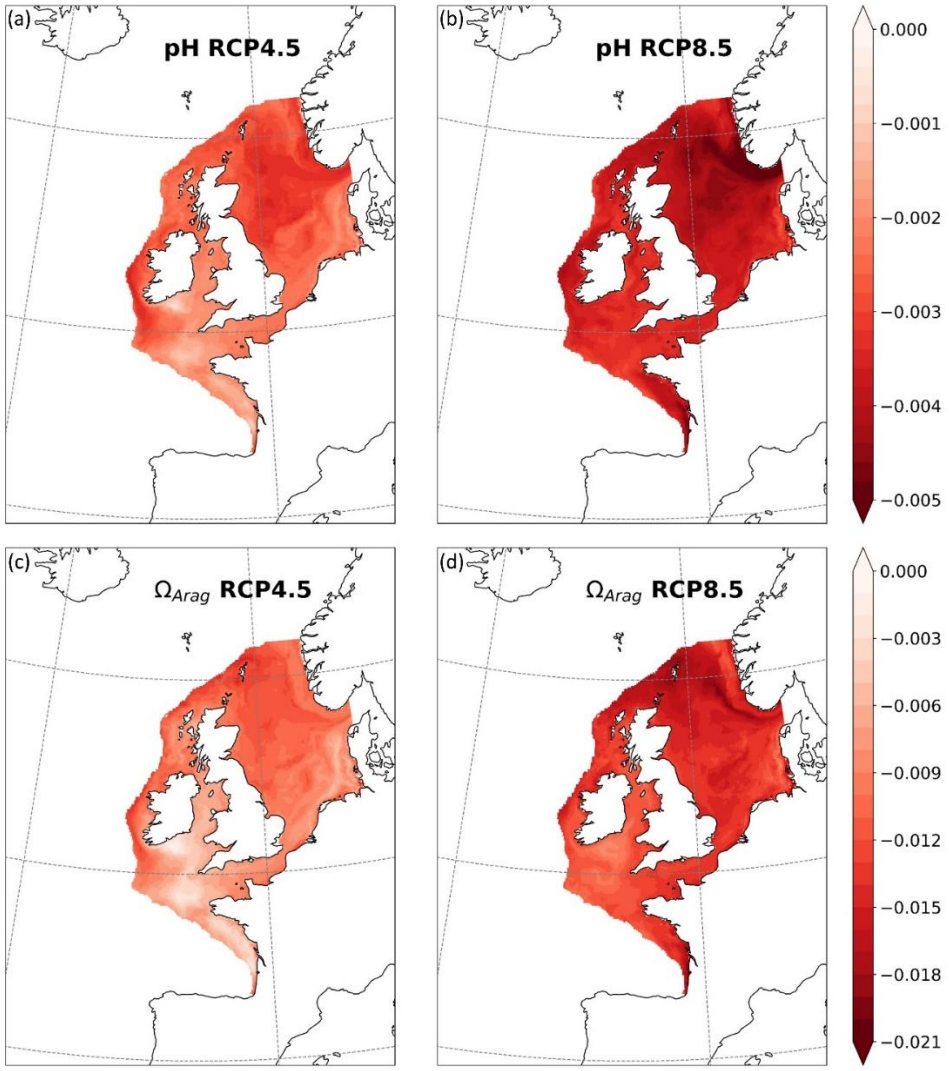


Figure 10: The trend of bottom water pH (top; yr^{-1}) and ΩArag (bottom; yr^{-1}) between 2015 and 2049 as projected by the AMM7-NEMO-ERSEM model under the RCP4.5 scenario (left) and RCP8.5 scenario (right) on the north-western shelf. Only data within the OSPAR regions II, II and IV has been shown. (McGovern et al., 2023)

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 the area of the seafloor that may experience undersaturation will range between 30% and 90% of the North-West European Shelf depending on the season (Figure 11).

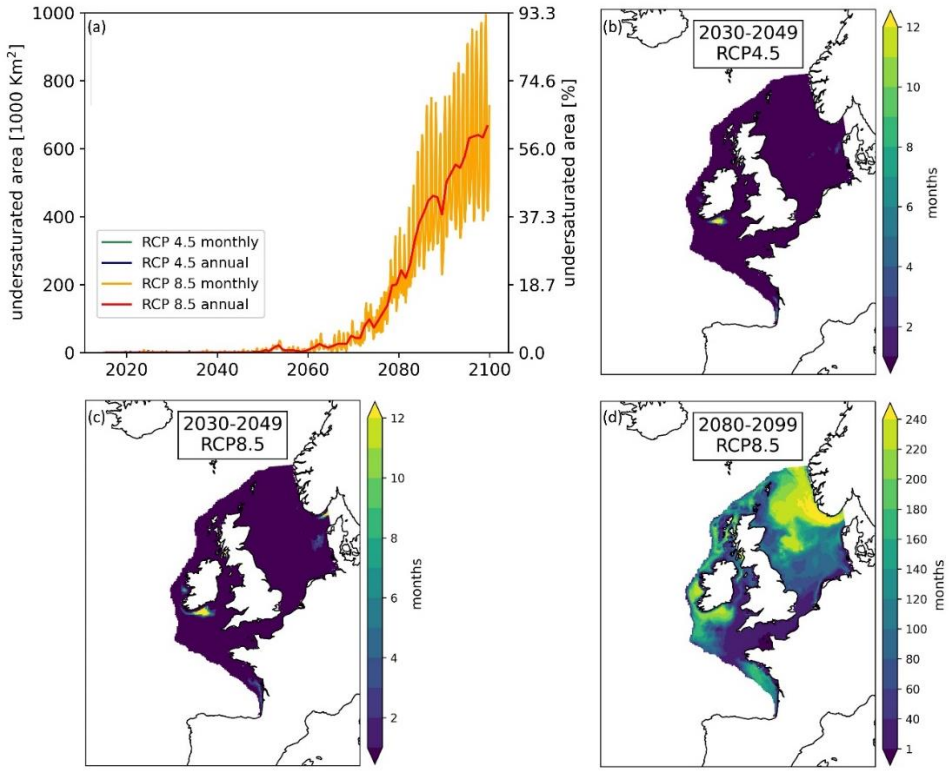


Figure 11: (a) Projection of the extent of aragonite undersaturation (Ω_{Arag}<1) in bottom water on the shelf from 2015 to 2099 (monthly and annual means). Note that data for RCP4.5 only extends until 2050 and they are all very low, close to the bottom axis. (b – d) Areas (and frequency) where aragonite undersaturation (Ω_{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 (McGovern et al., 2023).

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_2 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 (Baco et al., 2017; Davies and Guinotte, 2011), 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 (McGovern et al., 2023). 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.

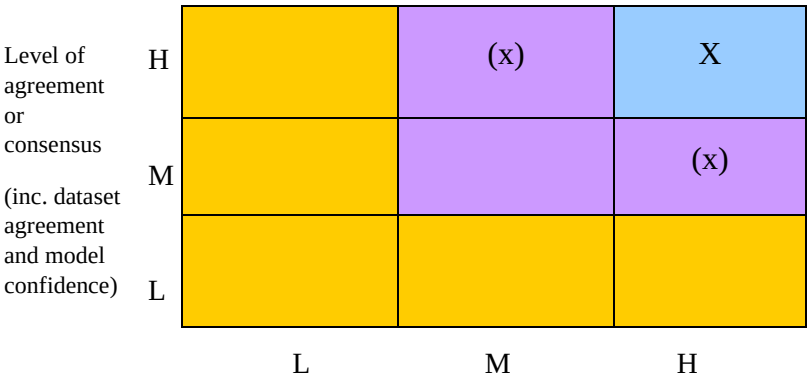
The high levels of variability within the nearshore, highlighted from the observational and modelling data, need to be taken into account when considering an organism's or ecosystem's response to ocean acidification. Organisms living within this high variability may already have mechanisms that allow 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. Importantly, 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.

Ocean acidification is also predicted to impact other biogeochemical processes, including nutrient cycling (e.g. Kitidis et al., 2011; Rees et al., 2017), climatically-important gases (Hopkins et al., 2020), and feedbacks to carbon cycling (Friedlingstein et al., 2024). However, there may also be less obvious impacts. For instance, modelling studies suggest that ocean acidification may decrease sound absorption at low frequencies (<10 kHz), with consequences for the ocean soundscape, although consensus is lacking (Hester et al., 2008; Ilyina et al., 2010; Possenti et al., 2023; Reeder and Chiu, 2010). These need further investigation, particularly around the UK and

NWES where there are already substantial levels of noise-influencing activities.

CONFIDENCE ASSESSMENT

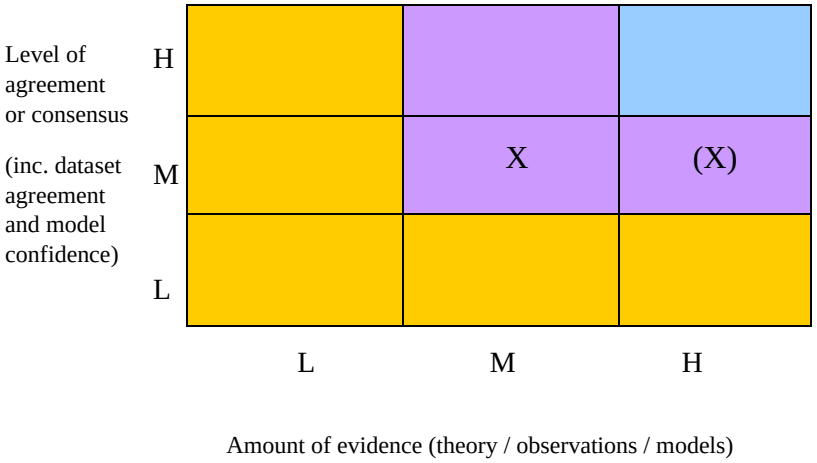
What is already happening?



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_2 exchange and the pH decline that result from anthropogenic CO_2 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?



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. The latest 2024 Nationally Determined Contributions (NDC) synthesis report suggests that the projected global mean temperatures are subject to significant uncertainty owing to the range of emission levels estimated for 2030 (51.5 [48.3–54.7] Gt CO_2eq) resulting from implementation of NDCs (including whether conditional elements are implemented or not). If there is full implementation of all announced targets including net zero targets, Long Term Strategies (LTS) and NDCs occurs, then optimistically, the estimated long-term per capita emissions of Parties are consistent with 2 °C scenarios (UNFCCC, 2024). However, significant further reductions in emissions (2-3 times) are required to achieve net zero CO_2 emissions by 2050 and to be consistent with limiting warming to 1.5 °C (UNFCCC, 2024).

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_2. 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. For example, there is uncertainty around the climate-change induced slowing of the Atlantic Meridional Ocean Circulation (AMOC), which is a basin-scale circulation pattern that influences oceanic CO_2 uptake in the North Atlantic. 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_2, 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. This is especially important as observations for surface CO_2 actually appear to be in decline: Dong et al., (2024) suggested a 35% decline from 2017-2021 in CO_2 observations (monthly fCO_2 data in SOCAT), leading to a 65% increase in the standard deviation of the calculated air-sea CO_2 flux.
    - 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 d 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. Uncertainty of model-derived products need to be assessed and, where possible, reduced. Some ways to address this would be to:
    - standardise procedures to include impacts of large scale ocean acidification in regional models, for instance moving from climatological boundary conditions (as used in current CMEMS reanalysis https://doi.org/10.48670/moi-00058) to imposing observed trends as done in the implementation reported here (fig. 5)
    - move for single simulations to ensemble of simulations, both for the recent past, but especially for future projections where the drivers of uncertainty increase due to multiple scenarios and multiple climate models with different climate sensitivity.
4. Data is not always readily available or compatible to bring together in the holistic 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 for 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 ocean acidification community thus allowing data harvesting and sharing between data archiving centres and data product generators (e.g. IOC, SOCAT, GLODAP).

REFERENCES

Agostini, S., Harvey, B.P., Wada, S., Kon, K., Milazzo, M., Inaba, K., Hall-Spencer, J.M., 2018. Ocean acidification drives community shifts towards simplified non-calcified habitats in a subtropical−temperate transition zone. Scientific Reports 8, 5–10. https://doi.org/10.1038/s41598-018-29251-7

Baco, A.R., Morgan, N., Roark, E.B., Silva, M., Shamberger, K.E.F., Miller, K., 2017. Defying Dissolution: Discovery of Deep-Sea Scleractinian Coral Reefs in the North Pacific. Scientific Reports 7, 1–11. https://doi.org/10.1038/s41598-017-05492-w

Bates, N.R., Astor, Y.M., Church, M.J., Currie, K., Dore, J.E., González-Dávila, M., Lorenzoni, L., Muller-Karger, F., Olafsson, J., Santana-Casiano, J.M., 2014. A time-series view of changing surface ocean chemistry due to ocean uptake of anthropogenic CO2 and ocean acidification. Oceanography 27, 126–141. https://doi.org/10.5670/oceanog.2014.16

Beaugrand, G., Mcquatters-Gollop, A., Edwards, M., Goberville, E., 2013. Long-term responses of North Atlantic calcifying plankton to

climate change. Nature Climate Change 3, 263–267. https://doi.org/10.1038/nclimate1753

Bednaršek, N., Feely, R.A., Howes, E.L., Hunt, B.P. V, Kessouri, F., León, P., Lischka, S., Maas, A.E., Mclaughlin, K., 2019. Systematic Review and Meta-Analysis Toward Synthesis of Thresholds of Ocean Acidification Impacts on Calcifying Pteropods and Interactions With Warming 6, 1–16. https://doi.org/10.3389/fmars.2019.00227

Birchenough, S., Williamson, P., Turley, C., 2017. Future of the Sea: Ocean Acidification. Foresight – Future of the Sea Evidence Review Foresight, Government Office for Science 19.

Birchenough, S.N.R., Reiss, H., Degraer, S., Mieszkowska, N., Borja, Á., Buhl-Mortensen, L., Braeckman, U., Craeymeersch, J., De Mesel, I., Kerckhof, F., Kröncke, I., Parra, S., Rabaut, M., Schröder, A., Van Colen, C., Van Hoey, G., Vincx, M., Wätjen, K., 2015. Climate change and marine benthos: A review of existing research and future directions in the North Atlantic. Wiley Interdisciplinary Reviews: Climate Change 6, 203–223. https://doi.org/10.1002/wcc.330

Breitbarth, E., Bellerby, R.J., Neill, C.C., Ardelan, M. V., Meyerhöfer, M., Zöllner, E., Croot, P.L., Riebesell, U., 2010. Ocean acidification affects iron speciation during a coastal seawater mesocosm experiment. Biogeosciences 7, 1065–1073. https://doi.org/10.5194/bg-7-1065-2010

Butenschön, M., Clark, J., Aldridge, J.N., Allen, J.I., Artioli, Y., Blackford, J., Bruggeman, J., Cazenave, P., Ciavatta, S., Kay, S., Lessin, G., van Leeuwen, S., 2016. ERSEM 15.06: a generic model for marine biogeochemistry and the ecosystem dynamics of the lower trophic levels. Geosci. Model Dev. 47.

Campen, H.I., Arévalo-Martínez, D.L., Artioli, Y., Brown, I.J., Kitidis, V., Lessin, G., Rees, A.P., Bange, H.W., 2022. The role of a changing Arctic Ocean and climate for the biogeochemical cycling of dimethyl sulphide and carbon monoxide. Ambio 51, 411–422. https://doi.org/10.1007/s13280-021-01612-z

Carstensen, J., Duarte, C.M., 2019. Drivers of pH Variability in Coastal Ecosystems. Environmental Science and Technology 53, 4020–4029. https://doi.org/10.1021/acs.est.8b03655

Chen, C.A., Lui, H., Hsieh, C., Yanagi, T., Kosugi, N., 2017. Deep oceans may acidify faster than anticipated due to global warming. Nature Climate Change 7, 890–895. https://doi.org/10.1038/s41558-017-0003-y

Curbelo-Hernández, D., Pérez, F.F., González-Dávila, M., Gladyshev, S.V., González, A.G., González-Santana, D., Velo, A., Sokov, A., Santana-Casiano, J.M., 2024. Ocean acidification trends and carbonate system dynamics across the North Atlantic subpolar gyre water masses during 2009–2019. Biogeosciences 21, 5561–5589. https://doi.org/10.5194/bg-21-5561-2024

Davies, A.J., Guinotte, J.M., 2011. Global habitat suitability for framework-forming cold-water corals. PLoS ONE 6. https://doi.org/10.1371/journal.pone.0018483

Demir, K.T., Mathis, M., Kossack, J., Liu, F., Daewel, U., Stegert, C., Thomas, H., Schrum, C., 2024. Variable organic matter stoichiometry enhances the biological drawdown of CO_2 in the Northwest European shelf seas. https://doi.org/10.5194/egusphere-2024-3449

Doney, S.C., Busch, D.S., Cooley, S.R., Kroeker, K.J., 2020. The impacts of ocean acidification on marine ecosystems and reliant human communities. Annual Review of Environment and Resources 45, 83–112. https://doi.org/10.1146/annurev-environ-012320-083019

Dong, Y., Bakker, D.C.E., Landschützer, P., 2024. Accuracy of Ocean CO_2 Uptake Estimates at a Risk by a Reduction in the Data Collection. Geophysical Research Letters 51, e2024GL108502. https://doi.org/10.1029/2024GL108502

Dutkiewicz, S., Morris, J.J., Follows, M.J., Scott, J., Levitan, O., Dyhrman, S.T., Berman-Frank, I., 2015. Impact of ocean acidification on the structure of future phytoplankton communities. Nature Climate Change 5, 1002–1006. https://doi.org/10.1038/nclimate2722

Findlay, H.S., Turley, C., 2021. Ocean acidification and climate change, in: Climate Change. Elsevier, pp. 251–279. https://doi.org/10.1016/b978-0-12-821575-3.00013-x

Fontela, M., Pérez, F.F., Carracedo, L.I., Padín, X.A., Velo, A., García-Ibañez, M.I., Lherminier, P., 2020. The Northeast Atlantic is running out of excess carbonate in the horizon of cold-water corals communities. Scientific Reports 10, 1–10. https://doi.org/10.1038/s41598-020-71793-2

Ford, D.J., Shutler, J.D., Blanco-Sacristán, J., Corrigan, S., Bell, T.G., Yang, M., Kitidis, V., Nightingale, P.D., Brown, I., Wimmer, W., Woolf, D.K., Casal, T., Donlon, C., Tilstone, G.H., Ashton, I., 2024. Enhanced ocean CO2 uptake due to near-surface temperature gradients. Nat. Geosci. 17, 1135–1140. https://doi.org/10.1038/s41561-024-01570-7

Fransner, F., Fröb, F., Tjiputra, J., Goris, N., Lauvset, S.K., Skjelvan, I., Jeansson, E., Omar, A., Chierici, M., Jones, E., Fransson, A., Ólafsdóttir, S.R., 2022. Acidification of the Nordic Seas. Biogeosciences 19, 979–1012. https://doi.org/doi:10.5194/bg-19-979-2022

Friedlingstein, P., O'Sullivan, M., Jones, M.W., Andrew, R.M., Hauck, J., Landschützer, P., Le Quéré, C., Li, H., Luijkx, I.T., Olsen, A., Peters, G.P., Peters, W., Pongratz, J., Schwingshackl, C., Sitch, S., Canadell, J.G., Ciais, P., Jackson, R.B., Alin, S.R., Arneth, A., Arora, V., Bates, N.R., Becker, M., Bellouin, N., Berghoff, C.F., Bittig, H.C., Bopp, L., Cadule, P., Campbell, K., Chamberlain, M.A., Chandra, N., Chevallier, F., Chini, L.P., Colligan, T., Decayeux, J., Djeutchouang, L., Dou, X., Duran Rojas, C., Enyo, K., Evans, W., Fay, A., Feely, R.A., Ford, D.J., Foster, A., Gasser, T., Gehlen, M., Gkritzalis, T., Grassi, G., Gregor, L., Gruber, N., Gürses, Ö., Harris, I., Hefner, M., Heinke, J., Hurtt, G.C., Iida, Y., Ilyina, T., Jacobson, A.R., Jain, A., Jarníková, T., Jersild, A., Jiang, F., Jin, Z., Kato, E., Keeling, R.F., Klein Goldewijk, K., Knauer, J., Korsbakken, J.I., Lauvset, S.K., Lefèvre, N., Liu, Z., Liu, J., Ma, L.,

Maksyutov, S., Marland, G., Mayot, N., McGuire, P., Metzl, N., Monacci, N.M., Morgan, E.J., Nakaoka, S.-I., Neill, C., Niwa, Y., Nützel, T., Olivier, L., Ono, T., Palmer, P.I., Pierrot, D., Qin, Z., Resplandy, L., Roobaert, A., Rosan, T.M., Rödenbeck, C., Schwinger, J., Smallman, T.L., Smith, S., Sospedra-Alfonso, R., Steinhoff, T., Sun, Q., Sutton, A.J., Séférian, R., Takao, S., Tatebe, H., Tian, H., Tilbrook, B., Torres, O., Tourigny, E., Tsujino, H., Tubiello, F., Van Der Werf, G., Wanninkhof, R., Wang, X., Yang, D., Yang, X., Yu, Z., Yuan, W., Yue, X., Zaehle, S., Zeng, N., Zeng, J., 2024. Global Carbon Budget 2024. https://doi.org/10.5194/essd-2024-519

García-Ibáñez, M.I., Zunino, P., Fröb, F., Carracedo, L.I., Ríos, A.F., Mercier, H., Olsen, A., Pérez, F.F., 2016. Ocean acidification in the subpolar North Atlantic: Rates and mechanisms controlling pH changes. Biogeosciences 13, 3701–3715. https://doi.org/10.5194/bg-13-3701-2016

González-Dávila, M., Santana-Casiano, J.M., 2023. Long-term trends of pH and inorganic carbon in the Eastern North Atlantic: the ESTOC site. Front. Mar. Sci. 10, 1236214. https://doi.org/10.3389/fmars.2023.1236214

Gregor, L., Shutler, J., Gruber, N., 2024. High-Resolution Variability of the Ocean Carbon Sink. Global Biogeochemical Cycles 38, e2024GB008127. https://doi.org/10.1029/2024GB008127

Hartman, S.E., Bett, B.J., Durden, J.M., Henson, S.A., Iversen, M., Jeffreys, R.M., Horton, T., Lampitt, R., Gates, A.R., 2021. Enduring science: Three decades of observing the Northeast Atlantic from the Porcupine Abyssal Plain Sustained Observatory (PAP-SO). Progress in Oceanography 191, 102508. https://doi.org/10.1016/j.pocean.2020.102508

Hartman, S.E., Humphreys, M.P., Kivimäe, C., Woodward, E.M.S., Kitidis, V., McGrath, T., Hydes, D.J., Greenwood, N., Hull, T., Ostle, C., Pearce, D.J., Sivyer, D., Stewart, B.M., Walsham, P., Painter, S.C., McGovern, E., Harris, C., Griffiths, A., Smilenova, A., Clarke, J., Davis, C., Sanders, R., Nightingale, P., 2019. Seasonality and spatial heterogeneity of the surface ocean carbonate system in the northwest European continental shelf. Progress in Oceanography 177, 101909. https://doi.org/10.1016/j.pocean.2018.02.005

Heiskanen, J., Brümmer, C., Buchmann, N., Calfapietra, C., Chen, H., Gielen, B., Gkritzalis, T., Hammer, S., Hartman, S., Herbst, M., Janssens, I.A., Jordan, A., Juurola, E., Karstens, U., Kasurinen, V., Kruijt, B., Lankreijer, H., Levin, I., Linderson, M., Loustau, D., Merbold, L., Myhre, C.L., Papale, D., Pavelka, M., Pilegaard, K., Ramonet, M., Rebmann, C., Rinne, J., Rivier, L., Saltikoff, E., Sanders, R., Steinbacher, M., Steinhoff, T., Watson, A., Vermeulen, A.T., Vesala, T., Vítková, G., Kutsch, W., 2021. The Integrated Carbon Observation System in Europe. Bulletin of the American Meteorological Society 855–872. https://doi.org/10.1175/BAMS-D-19-0364.1

Hester, K.C., Peltzer, E.T., Kirkwood, W.J., Brewer, P.G., 2008. Unanticipated consequences of ocean acidification: A noisier ocean

at lower pH. Geophysical Research Letters 35, 2008GL034913. https://doi.org/10.1029/2008GL034913

Hoegh-Guldberg, O., Poloczanska, E.S., Skirving, W., Dove, S., 2017. Coral reef ecosystems under climate change and ocean acidification. Frontiers in Marine Science 4. https://doi.org/10.3389/fmars.2017.00158

Hopkins, F.E., Suntharalingam, P., Gehlen, M., Andrews, O., Archer, S.D., Bopp, L., Buitenhuis, E., Dadou, I., Duce, R., Goris, N., Jickells, T., Johnson, M., Keng, F., Law, C.S., Lee, K., Liss, P.S., Lizotte, M., Malin, G., Murrell, J.C., Naik, H., Rees, A.P., Schwinger, J., Williamson, P., 2020. The impacts of ocean acidification on marine trace gases and the implications for atmospheric chemistry and climate. Proceedings of the Royal Society A: Mathematical, Physical and Engineering Sciences 476. https://doi.org/10.1098/rspa.2019.0769

Humphreys, M.P., Griffiths, A.M., Achterberg, E.P., Holliday, N.P., Rérolle, V.M.C., Menzel Barraqueta, J.L., Couldrey, M.P., Oliver, K.I.C., Hartman, S.E., Esposito, M., Boyce, A.J., 2016. Multidecadal accumulation of anthropogenic and remineralized dissolved inorganic carbon along the Extended Ellett Line in the northeast Atlantic Ocean. Global Biogeochemical Cycles 30, 293–310. https://doi.org/10.1002/2015GB005246

Ilyina, T., Zeebe, R.E., Brewer, P.G., 2010. Future ocean increasingly transparent to low-frequency sound owing to carbon dioxide emissions. Nature Geoscience 3, 18–22. https://doi.org/10.1038/ngeo719

IPCC, 2021. Summary for Policymakers, in: Masson-Delmotte, V., Zhai, P., Pirani, A., Connors, S.L., Péan, C., Berger, S., Caud, N., Chen, Y., Goldfarb, L., Gomis, M.I., Huang, M., Leitzell, K., Lonnoy, E., Matthews, J.B.R., Maycock, T.K., Waterfield, T., Yelekçi, O., Yu, R., B, Z. (Eds.), Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, Cambridge.

Jackson, E.L., Davies, A.J., Howell, K.L., Kershaw, P.J., Hall-Spencer, J.M., 2014. Future-proofing marine protected area networks for cold water coral reefs. 2ICES Journal of Marine Science 71, 2621–2629. https://doi.org/10.1093/icesjms/fsu099

Jones, E., Chierici, M., Skjelvan, I., Norli, M., Frigstad, H., Børsheim, K.Y., Lødemel, H.H., Kutti, T., King, A.L., Sørensen, K., Lauvset, S.K., Jackson-Misje, K., Apelthun, L.B., de Lange, T., Johannsessen, T., Mourgues, C., Bellerby, R.G.J., 2020. Monitoring ocean acidification in Norwegian seas in 2019. Institute of Marine Research, NORCE Norwegian Research Centre, University of Bergen, Norwegian Institute for Water Research, Bergen.

Khatiwala, S., Tanhua, T., Mikaloff Fletcher, S., Gerber, M., Doney, S.C., Graven, H.D., Gruber, N., McKinley, G.A., Murata, A., Ríos, A.F., Sabine, C.L., 2013. Global ocean storage of anthropogenic carbon. Biogeosciences 10, 2169–2191. https://doi.org/10.5194/bg-10-2169-2013

Kitidis, V., Brown, I., Hardman-Mountford, N., Lefèvre, N., 2017. Surface ocean carbon dioxide during the Atlantic Meridional Transect (1995–2013); evidence of ocean acidification. Progress in Oceanography 158, 65–75. https://doi.org/10.1016/j.pocean.2016.08.005

Kitidis, V., Laverock, B., McNeill, L.C., Beesley, A., Cummings, D., Tait, K., Osborn, M.A., Widdicombe, S., 2011. Impact of ocean acidification on benthic and water column ammonia oxidation. Geophysical Research Letters 38, 2–6. https://doi.org/10.1029/2011GL049095

Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M., Gattuso, J.P., 2013. Impacts of ocean acidification on marine organisms: Quantifying sensitivities and interaction with warming. Global Change Biology 19, 1884–1896. https://doi.org/10.1111/gcb.12179

Landschützer, P., Gruber, N., Bakker, D.C.E., 2016. Decadal variations and trends of the global ocean carbon sink. Global Biogeochemical Cycles 30, 1396–1417. https://doi.org/10.1002/2015GB005359

Landschützer, P., Gruber, N., Bakker, D.C.E., Stemmler, I., Six, K.D., 2018. Strengthening seasonal marine CO2 variations due to increasing atmospheric CO2. Nature Climate Change 8, 146–150. https://doi.org/10.1038/s41558-017-0057-x

Le Quesne, W.J.F., Pinnegar, J.K., 2012. The potential impacts of ocean acidification: Scaling from physiology to fisheries. Fish and Fisheries 13, 333–344. https://doi.org/10.1111/j.1467-2979.2011.00423.x

León, P., Bednaršek, N., Walsham, P., Cook, K., Hartman, S.E., Wall-Palmer, D., Hindson, J., MacKenzie, K., Webster, L., Bresnan, E., 2020. Relationship between shell integrity of pelagic gastropods and carbonate chemistry parameters at a Scottish Coastal Observatory monitoring site. ICES Journal of Marine Science 77, 436–450. https://doi.org/10.1093/icesjms/fsz178

Ma, D., Gregor, L., Gruber, N., 2023. Four Decades of Trends and Drivers of Global Surface Ocean Acidification. Global Biogeochemical Cycles 37, e2023GB007765. https://doi.org/10.1029/2023GB007765

Macovei, V.A., Hartman, S.E., Schuster, U., Torres-Valdés, S., Moore, C.M., Sanders, R.J., 2020. Impact of physical and biological processes on temporal variations of the ocean carbon sink in the mid-latitude North Atlantic (2002–2016). Progress in Oceanography 180. https://doi.org/10.1016/j.pocean.2019.102223

Madec, G., team, the N., 2016. NEMO ocean engine, Note du Pôle de modélisation, Institut Pierre-Simon Laplace (IPSL). France.

Mangi, S.C., Lee, J., Pinnegar, J.K., Law, R.J., Tyllianakis, E., Birchenough, S.N.R., 2018. The economic impacts of ocean acidification on shellfish fisheries and aquaculture in the United Kingdom. Environmental Science and Policy 86, 95–105. https://doi.org/10.1016/j.envsci.2018.05.008

McEvoy, A.J., Atkinson, A., Airs, R.L., Brittain, R., Brown, I., Fileman, E.S., Findlay, H.S., McNeill, C.L., Ostle, C., Smyth, T.J., Somerfield, P.J., Tait, K., Tarran, G.A., Thomas, S., Widdicombe,

C.E., Woodward, E.M.S., Beesley, A., Conway, D.V.P., Fishwick, J., Haines, H., Harris, C., Harris, R., Hélaouët, P., Johns, D., Lindeque, P.K., Mesher, T., McQuatters-Gollop, A., Nunes, J., Perry, F., Queiros, A.M., Rees, A., Rühl, S., Sims, D., Torres, R., Widdicombe, S., 2023. The Western Channel Observatory: a century of physical, chemical and biological data compiled from pelagic and benthic habitats in the western English Channel. Earth Syst. Sci. Data 15, 5701–5737. https://doi.org/10.5194/essd-15-5701-2023

McGovern, E., Schilder, J., Artioli, Y., Birchenough, S., Dupont, S., Findlay, H., Skjelvan, I., Skogen, M.D., Álvarez, M., Büsher, J.V., Chierici, M., Aagaard Christensen, J.P., Diaz, P.L., Grage, A., Gregor, L., Humphreys, M., Järnegren, J., Knockaert, M., Krakau, M., Nogueira, M., Ólafsdóttir, S.R., von Schuckmann, K., Carreiro-Silva, M., Stiasny, M., Walsham, P., Widdicombe, S., Gehlen, M., Chau, T.T.T., Chevallier, F., Savoye, N., Clark, J., Galli, G., Hordoir, R., Moffat, C., 2023. OSPAR Quality Status report 2023: ocean acidification.

McGrath, T., Kivimäe, C., Tanhua, T., Cave, R.R., McGovern, E., 2012. Inorganic carbon and pH levels in the Rockall Trough 1991-2010. Deep-Sea Research Part I: Oceanographic Research Papers 68, 79–91. https://doi.org/10.1016/j.dsr.2012.05.011

McKinley, G.A., Fay, A.R., Lovenduski, N.S., Pilcher, D.J., 2017. Natural Variability and Anthropogenic Trends in the Ocean Carbon Sink. Annual Review of Marine Science 9, 125–150. https://doi.org/10.1146/annurev-marine-010816-060529

Olafsson, J., Olafsdottir, S.R., Benoit-Cattin, A., Danielsen, M., Arnarson, T.S., Takahashi, T., 2009. Rate of Iceland Sea acidification from time series measurements. Biogeosciences 6, 2661–2668. https://doi.org/10.5194/bg-6-2661-2009

Pérez, F.F., Fontela, M., García-Ibáñez, M.I., Mercier, H., Velo, A., Lherminier, P., Zunino, P., De La Paz, M., Alonso-Pérez, F., Guallart, E.F., Padin, X.A., 2018. Meridional overturning circulation conveys fast acidification to the deep Atlantic Ocean. Nature 554, 515–518. https://doi.org/10.1038/nature25493

Pérez, F.F., Olafsson, J., Ólafsdóttir, S.R., Fontela, M., Takahashi, T., 2021. Contrasting drivers and trends of ocean acidification in the subarctic Atlantic. Scientific Reports 11, 1–16. https://doi.org/10.1038/s41598-021-93324-3

Possenti, L., Reichart, G.-J., de Nooijer, L., Lam, F.-P., de Jong, C., Colin, M., Binnerts, B., Boot, A., von der Heydt, A., 2023. Predicting the contribution of climate change on North Atlantic underwater sound propagation. PeerJ 11, e16208. https://doi.org/10.7717/peerj.16208

Rastelli, E., Petani, B., Corinaldesi, C., Dell'Anno, A., Lo Martire, M., Cerrano, C., Danovaro, R., 2020. A high biodiversity mitigates the impact of ocean acidification on hard-bottom ecosystems. Scientific Reports 10. https://doi.org/10.1038/s41598-020-59886-4

Raven, J., Caldeira, K., Elderfield, H., Hoegh-Guldberg, O., Liss, P., Riebesell, U., Shepherd, J., Turley, C., Watson, A., 2005. Ocean acidification due to increasing atmospheric carbon dioxide. The Royal Society, London, UK.

Reeder, D.B., Chiu, C.-S., 2010. Ocean acidification and its impact on ocean noise: Phenomenology and analysis. The Journal of the Acoustical Society of America 128, EL137–EL143. https://doi.org/10.1121/1.3431091

Rees, A.P., Turk-Kubo, K.A., Al-Moosawi, L., Alliouane, S., Gazeau, F., Hogan, M.E., Zehr, J.P., 2017. Ocean acidification impacts on nitrogen fixation in the coastal western Mediterranean Sea. Estuarine, Coastal and Shelf Science 186, 45–57. https://doi.org/10.1016/j.ecss.2016.01.020

Sabine, C.L., Feely, R.A., Gruber, N., Key, R.M., Lee, K., Bullester, J.L., Wanninkhof, R., Wong, C.S., Wallace, D.W.R., Tilbrook, B., Millero, F.J., Peng, T.-H., Kozyr, A., Ono, T., Rios, A.F., 2004. The oceanick sink for anthtopogenic CO2. Science 305, 367–371.

Schlunegger, S., Rodgers, K.B., Sarmiento, J.L., Frölicher, T.L., Dunne, J.P., Ishii, M., Slater, R., 2019. Emergence of anthropogenic signals in the ocean carbon cycle. Nature Climate Change 9, 719–725. https://doi.org/10.1038/s41558-019-0553-2

Sims, R.P., Bedington, M., Schuster, U., Watson, A., Kitidis, V., Torres, R., Findlay, H., Fishwick, J., Brown, I., Bell, T., 2021. Tidal mixing of estuarine and coastal waters in the Western English Channel controls spatial and temporal variability in seawater CO₂ Biogeosciences Discussions 1–25.

Skjelvan, I., Jones, E., Chierici, M., Frigstad, H., Borsheim, K.Y., Lodemel, H.H., Kutti, T., King, A.L., Sorensen, K., Omar, A., Bellerby, R.G.J., Christensen, G., Marty, S., Protsenko, E., Mengeot, C., Valestrand, L., Norli, M., Jackson-Misje, K., Apelthun, L.B., de Lange, T., Johannessen, T., Mourgues, C., 2021. Monitoring ocean acidification in Norwegian seas in 2020. NORCE Norwegian Research Centre, Institute of Marine Research, Norwegian Institute for Water Research, University of Bergen, Bergen.

Skjelvan, I., Lauvset, S.K., Johannessen, T., Gundersen, K., Skagseth, Ø., 2022. Decadal trends in Ocean Acidification from the Ocean Weather Station M in the Norwegian Sea. Journal of Marine Systems 2234, 103775. https://doi.org/doi: 10.1016/j.jmarsys.2022.103775 Received

Thomas, H., Bozec, Y., Elkalay, K., De Baar, H.J.W., 2004. Enhanced Open Ocean Storage of CO2 from Shelf Sea Pumping. Science 304, 1005–1008. https://doi.org/10.1126/science.1095491

Townhill, B., Artioli, Y., Pinnegar, J., Birchenough, S.N.R., 2022. Exposure of commercial shellfish to changing pH levels: how to scale-up experimental evidence to regional impacts. ICES Journal of Marine Science.

UNFCCC, 2024. Nationally determined contributions under the Paris Agreement: Synthesis report by the secretariat.

Vázquez-Rodríguez, M., Pérez, F.F., Velo, A., Ríos, A.F., Mercier, H., 2012. Observed acidification trends in North Atlantic water masses. Biogeosciences 9, 5217–5230. https://doi.org/10.5194/bg-9-5217-2012

Wannicke, N., Frey, C., Law, C.S., Voss, M., 2018. The response of the marine nitrogen cycle to ocean acidification. Global Change Biology 24, 5031–5043. https://doi.org/10.1111/gcb.14424

Watson, A.J., Schuster, U., Shutler, J.D., Holding, T., Ashton, I.G.C., Landschützer, P., Woolf, D.K., Goddijn-Murphy, L., 2020. Revised estimates of ocean-atmosphere CO2 flux are consistent with ocean carbon inventory. Nature Communications 11, 1–6. https://doi.org/10.1038/s41467-020-18203-3

Yin, T., Papadimitriou, S., Rérolle, V.M.C., Arundell, M., Cardwell, C.L., Walk, J., Palmer, M.R., Fowell, S.E., Schaap, A., Mowlem, M.C., Loucaides, S., 2021. A novel lab-on-chip spectrophotometric pH sensor for autonomous in situ seawater measurements to 6000 m depth on stationary and moving observing platforms. Environmental Science & Technology 55, 14968–14978. https://doi.org/10.1021/acs.est.1c03517

Zhu, K., Hopwood, M.J., Groenenberg, J.E., Engel, A., Achterberg, E.P., Gledhill, M., 2021. Influence of pH and Dissolved Organic Matter on Iron Speciation and Apparent Iron Solubility in the Peruvian Shelf and Slope Region. Environmental Science and Technology 55, 9372–9383. https://doi.org/10.1021/acs.est.1c02477

Zunino, S., Canu, D.M., Bandelj, V., Solidoro, C., 2017. Effects of ocean acidification on benthic organisms in the Mediterranean Sea under realistic climatic scenarios: A meta-analysis. Regional Studies in Marine Science 10, 86–96. https://doi.org/10.1016/j.rsma.2016.12.011