Recommendations to inform a UK Ocean Acidification Monitoring Strategy

Report by the Ocean Acidification sub group of the Science Advisory Council

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Executive summary

Rationale for report

Ocean acidification (OA) is the increase in seawater acidity primarily driven by rising atmospheric carbon dioxide. There is now incontrovertible evidence that OA is occurring on a global scale, affecting other important aspects of marine chemistry and with potentially significant adverse consequences on marine life and human society. However, many uncertainties remain relating to the current status and future development of OA at the regional and local scale, and its interactions with other marine environmental stresses such as warming and de-oxygenation. Well-designed and well-coordinated OA monitoring in UK marine waters, in those of UK Overseas Territories (UKOTs), and more widely, in collaboration with Commonwealth partners and others, will help to quantify these linked changes, and to improve assessments of their future ecological and socio-economic impacts.

The UK government has previously recognised the need for OA observations and research through its co-support, with the Natural Environment Research Council, of the UK Ocean Acidification (UKOA) research programme. The UK has also supported the inclusion of OA monitoring in OSPAR (Convention for the Protection of the Marine Environment of the North East Atlantic); in UN Sustainable Development Goals; in the Commonwealth Blue Charter, and through other international policy initiatives.

This report to the Department for Environment, Food and Rural Affairs (Defra) provides a framework for a national OA monitoring strategy, building on the UKOA programme. It has been prepared by a sub-group of Defra's Science Advisory Council (SAC), tasked with reviewing the current national monitoring and assessment programmes for OA and providing advice on where the UK can contribute to global OA monitoring. The group was asked to give particular attention to:

- Identifying and exploiting locations where long-term monitoring could take place in the UK, UK Overseas Territories and the Commonwealth.
- The role of developing technologies for reducing the costs of making measurements.

Ten recommendations (see below) identify actions to deliver relevant information for policy development in these topic areas, giving particular attention to cost-effectiveness.

Key review outcomes

The UK has considerable expertise in OA research and observations, with many well-established scientific linkages on a worldwide basis. The scientific community's previous work has confirmed that increasing atmospheric CO_2 causes a decrease in seawater pH (increase in hydrogen ion concentration; acidity) together with several other chemical changes, including a decrease in carbonate saturation. It has also shown that high-quality measurements of other parameters, made consistently over relatively long time periods, are needed to distinguish CO_2-driven long term trends from other factors causing natural OA variability over time and space. Such variability is particularly high in coastal waters, with strong biological seasonality and riverine influences.

Policy-relevant OA monitoring not only needs to provide reliable information on current status and the long-term trend of multiple carbonate chemistry parameters, but also on their temporal and spatial variability. All these aspects are potentially important to marine organisms, with economically-damaging impacts already occurring in some countries. Vulnerable species include calcifying plankton and seafloor invertebrates, such as cold water corals around the UK shelf and coral reefs in UKOTs.

Good progress has been made by UK research groups, and others, in developing and deploying autonomous sensors for pH and other OA-relevant parameters. Such instrumentation is now playing an increasing role in spatial surveys and measurements at remote locations; further technological developments should be supported in this regard (see *Recommendations 1 and 8*). Nevertheless, for time-series studies and calibration of other measurements, there is continued need for discrete water sampling with laboratory-based analyses together with the collection, where possible, of supplementary information to assist interpretation (*Recommendation 2*). At least one UK laboratory should be supported to carry out such OA measurements for the proposed monitoring network to the required international standards (*Recommendation 3*).

Computer models can be used to project future acidification conditions over the full depth of the open ocean, also in shelf seas and at coastal sites, for different CO_2 emission scenarios. National capabilities in OA modelling are now being developed to take account of the wide range of physical, chemical and biological factors involved. Such modelling can provide temporal projections and spatial interpolations, yet does not replace the need for sustained observations. Indeed, an important role of the UK OA observation network is to test and improve model performance at national, regional and global scales. Making high-quality data available to others (*Recommendation 4*) provides associated leadership opportunities for wider international coordination and collaboration (*Recommendation 5*).

Four UK sites where OA measurements are ongoing or have previously been made provide a sound basis for a future national network (*Recommendation 6*), with at least two additional time-series sites recommended to widen habitat coverage (*Recommendation 7*). Survey-based sampling on research cruises and possibly on commercial vessels offers a cost-effective mechanism to obtain additional information on spatial variation of carbonate chemistry conditions, and to elucidate the possible causes of that variation, in the North East Atlantic and further afield (*Recommendation 8*).

UKOTs provide a timely and scientifically-valuable opportunity to extend the geographic coverage of OA monitoring, in the context of global gaps and potential impacts on OA-sensitive ecosystems. Relevant advice takes account of these factors, also the presence (or absence) of existing scientific infrastructure and expertise (*Recommendation 9*).

The development of a core infrastructure for OA monitoring in the UK (*Recommendation 3*) can also provide a centre of excellence to provide training, advice, capacity building and knowledge exchange with Commonwealth countries (e.g. through the Commonwealth Blue Charter) and more widely, supporting the development of their own OA monitoring programmes (*Recommendation 10*).

Recommendations

1. **The UK should make further investment in sensor development for ocean acidification monitoring.** Such work should build on existing R&D work in developing automatic methods and technologies for carbonate chemistry measurements; it should also promote the worldwide commercial exploitation of such innovations, through both UKRI and government support.

2. **UK ocean acidification monitoring should follow international quality standards, based on a suite of core physico-chemical measurements and preferably in the context of additional ecological information.** Most time series should be based on discrete water samples, analysed for at least two of the four core carbonate chemistry variables (pH, pCO_2, DIC and TA) as well as temperature, salinity, oxygen and nutrients. Such monitoring should, where feasible, also involve or be aligned with the collection of information on other important biogeochemical and ecological variables such as bio-optical parameters, chlorophyll, and pelagic and benthic community composition.

3. **A nationally-funded facility for quality-controlled carbonate chemistry analyses should be established**, based on one or more centres of excellence and wider networking. This facility will use accepted international standard reference materials, carry out inter-calibration exercises, and provide national and international training.

4. **UK ocean acidification monitoring data should be suitably archived and made freely and rapidly available to other users**. Data should be collected and archived in line with the Marine Data Information Network (MEDIN) principles in a UK data archive centre and made available via the data portal of the Global Ocean Acidification Observing Network (GOA-ON). Regular reporting of data syntheses is encouraged; e.g. through the Marine Climate Change Impacts Partnership (MCCIP).

5. **National support should be made available to assist scientific involvement in the GOA-ON initiative**. This should include attendance at international meetings and support for hosting the regional GOA-ON hub for the North East Atlantic and Europe.

6. **The existing four UK time series for ocean acidification should be maintained, on a long-term basis**. These sites comprise the Western Channel Observatory, Stonehaven and two North Sea SmartBuoys. The frequency of direct sampling at the SmartBuoys should be increased from quarterly to monthly.

7. **Additional UK sites for ocean acidification monitoring should be established, to cover other important habitats.** In addition to the Loch Ewe site, currently being established by Marine Scotland, fixed sampling sites (covering the full water depth) should be considered in seasonally-stratified areas such as the northern North Sea or the Irish Sea.

8. **The spatial coverage of ocean acidification observations should be further increased by using new technologies to link with other marine monitoring activities in UK waters and more widely**. Cost-effective opportunities exist to include routine ocean acidification monitoring in the sampling undertaken along the Ellet Line, in the Faroe-Scotland Channel, along the Atlantic Meridional Transect (AMT), by Continuous Plankton Recorders (CPRs), at the Porcupine Abyssal Plain (PAP) site in the North Atlantic, and by the deployment of instrumented Argo floats.

9. **Existing ocean acidification monitoring initiatives in UK Overseas Territories (UKOTs) should be supported, and further consideration given to the establishment of additional sites**. In addition to strengthened links with well-established OA monitoring at Bermuda, opportunities exist for knowledge exchange in other UKOTs (e.g. in Caribbean) through training of support staff, provision of standards, inter-calibration exercises, and use of UK analytic facilities. There is scope to extend, and improve the value of, current OA observations in the British Antarctic Territories and the British Indian Ocean Territory (BIOT), and for new sites to be established in Pitcairn, St Helena and Tristan da Cunha.

10. **The proposed UK core facilities for OA analyses, data archiving and associated infrastructure should be used to offer training, support and opportunities for knowledge exchange with Commonwealth countries interested in OA monitoring.**

1. Introduction

1.1 Task

The Science Advisory Council (SAC) of the Department for Environment, Food and Rural Affairs (Defra), was tasked with assessing the potential for UK-led Ocean Acidification (OA) monitoring, both in territorial waters of the UK and UK Overseas Territories (UKOTs), the potential for collaboration with Commonwealth countries on OA monitoring and with respect to the technology required to deliver this monitoring. This request follows an inquiry into OA held by the Parliamentary Science and Technology Committee in 2017. The inquiry commended the recent research on OA led by the UK but raised concerns about the long-term observing of OA in UK shelf waters and in the UKOTs. There is also a requirement for the UK to address OA under Sustainable Development Goal 14.3[1] and this will require a monitoring programme. In this context, the SAC was asked to consider how the UK could develop such an observing system, and to provide options that could be considered for improving the current monitoring of OA.

The UK government has previously recognised the need for OA observations and research through its co-support, with the Natural Environment Research Council, of the UK Ocean Acidification (UKOA) research programme. The UK has also supported the inclusion of OA monitoring in OSPAR (Convention for the Protection of the Marine Environment of the North East Atlantic); in UN Sustainable Development Goals; in the Commonwealth Blue Charter, and through other international policy initiatives.

Monitoring of OA needs to be sufficient for reliable quantification of the magnitude, spatial scales and rate of changes in pH and associated conditions. There is a need not only to obtain information on long-term trends (with global causes, mostly rising atmospheric carbon dioxide) but also on short-term variability (with local and regional causes, mostly biological and physical), since both changes have potential consequences for marine organisms in the context of other stressors, e.g. rising sea temperature, habitat loss. OA observations need to be closely linked with other monitoring of the marine environment to facilitate integrated policy responses which will safeguard marine ecosystems.

To deliver independent expert advice to meet this request, a sub group of the SAC was convened, formed of relevant experts in the field of ocean science and working closely with the Defra marine evidence team. The Terms of Reference (Appendix 2) describe the aims of the sub group which are to consider the contribution to global OA monitoring the UK can make by:

1. Identifying and exploiting locations where long-term monitoring could take place in the UK, UK Overseas Territories and the Commonwealth.

2. Developing and supplying technology for reducing the costs of making measurements.

This report presents the rationale for monitoring OA and the techniques and the technology required to do this in Section 1. The current situation with regards to monitoring effort in the UK and the technology available, are discussed in Section 2, culminating in recommendations for priority sites and approaches for OA monitoring to support evidence requirements for UK marine policy development. A similar discussion of activities and opportunities for OA monitoring in UK Overseas Territories (UKOTs) is presented in Section 3. The report concludes with some high level comments regarding engagement

[1] https://sustainabledevelopment.un.org/content/documents/11803Official-List-of-Proposed-SDG-Indicators.pdf

with Commonwealth Countries, Section 4, and an overarching summary of the recommendations made by the sub group for delivering UK-led OA monitoring, Section 5.

1.2 The process of ocean acidification and its impacts

Atmospheric carbon dioxide (CO_2) concentrations are increasing as a result of fossil fuel combustion, other industrial emissions and land use changes. The cumulative atmospheric increase of CO_2 is partly ameliorated through the uptake of CO_2 by both the terrestrial biosphere and by the ocean. Around 25% of anthropogenic CO_2 emissions (2.6 Gigatonnes of carbon per year) has been taken up by the global ocean (Le Quere et al., 2015). Appendix 3 describes in further detail, the process of ocean acidification and the complexities of the interactions between the marine carbonate chemistry and marine organisms.

It is very likely that this process of ocean acidification will have major impacts on marine ecosystems. Evidence from the many laboratory studies of the biological impacts of OA has shown that many species are negatively affected; however, a small number of organisms show no response to OA whilst others may apparently benefit (Kroeker et al., 2013, Wittmann and Portner, 2013). OA will increase the stress on many marine species, particularly those which create calcium carbonate ($CaCO_3$) shells and external structures (this includes many species of phytoplankton, crustaceans and molluscs as well as cold water corals), as these organisms will have to expend greater energy to produce and maintain their exoskeletons in lower pH waters (Sunday et al., 2017). Damage is also anticipated to many commercial fisheries as demonstrated in the Centre for Environment, Fisheries and Aquaculture Science (Cefas) Defra supported PLACID programme[2]. The impacts of OA must be also be evaluated in the context of multiple stresses on marine ecosystems (Riebesell and Gattuso, 2015) imposed by human activities such as increased temperature, nutrient loading, de-oxygenation, pollution (including plastics) and introduction of non-native, invasive species. The UK requires a monitoring network to understand the scale of challenge its marine waters are facing from developing ocean acidification and to develop policy responses to these challenges.

1.3 Measuring ocean acidification

At open-ocean sites, the process of OA is progressive and steady, due to increasing atmospheric CO_2 concentrations. Whilst the rate may be influenced by local or regional factors (Duarte et al., 2013), the annual average decrease in seawater pH is around 0.002 per year on a background pH of about 8 as demonstrated at some open ocean monitoring

[2] Placing Ocean Acidification in Wider Fisheries Context (2017) Birchenough S.N.R., Williamson, P. and Turley C. Futures of the Sea: Ocean Acidification *https://www.gov.uk/government/publications/future-of-the-sea-ocean-acidification*).

sites (Figure 1). This scale and rate of ocean acidification will by the end of the century be greater than has been seen in the marine environment for millions of years.

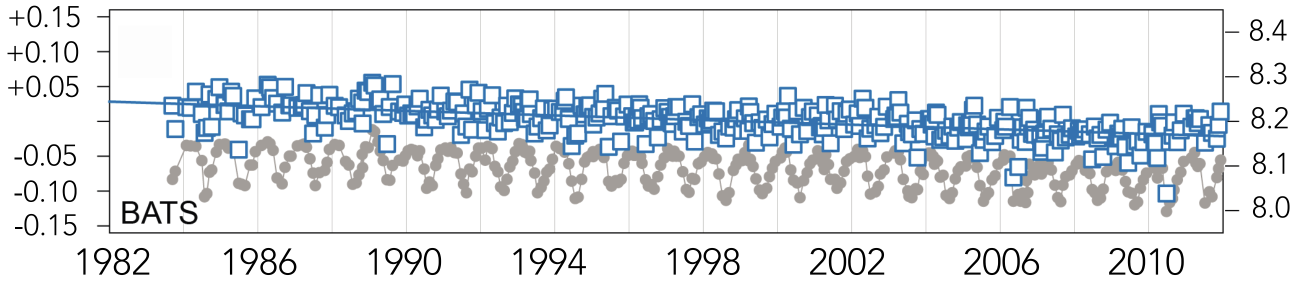

Figure 1: A time-series of changing ocean pH at the Bermuda Atlantic time-series study (BATS) site showing the long-term trend in the open ocean.

The grey symbols are the actual pH data and show a seasonal change of about 0.1 pH units superimposed on a long term decline (right axis applies with actual pH). The blue squares remove the seasonality to show the long-term decrease in pH of about 0.002 per year (left hand axis which is offset and shows the change in pH). For further details see Bates et al. (2014).

The pH change is challenging to measure directly with appropriate accuracy and precision. Although the quality of direct *in situ* pH measuring devices (sensors) which can be deployed autonomously in seawater has greatly improved in recent years, most programmes measuring long term OA trends do not rely on sensors, but instead use the approach of collecting and preserving water samples, and then measuring at least two other components of the marine carbonate system: dissolved inorganic carbon (DIC)[3], total alkalinity (TA)[4] and partial pressure of CO_2 (pCO_2)[5]. Such measurements allow pH (and all other components of the marine carbonate system) to be determined. It is standard practice to also measure other physico-chemical parameters (including temperature, salinity and oxygen) to provide a context for interpreting OA measurements.

The time-series records of OA on the UK shelf seas[6] are shorter than at several open ocean stations, (e.g. Bermuda), and individual stations do not yet show unambiguous evidence of acidification: however, there is a significant long-term acidification trend for the North West European shelf[7] as a whole (Ostle et al., 2016). There is greater temporal variability in seawater pH in coastal waters (Figure 2), with the seasonal range being around twice that typically observed in the open ocean. These seasonal cycles of pH are

[3] Dissolved inorganic carbon: (DIC) the sum of all inorganic carbon ions in the seawater
[4] Total alkalinity (TA): a measure of the capacity of the water sample to react with hydrogen ions
[5] pCO_2: a measure of the concentration of dissolved CO_2 in the seawater which can also be expressed as fugacity of dissolved CO2 (or fCO2)
[6] Regions around the UK with water depths less than 200m
[7] Placing Ocean Acidification in Wider Fisheries Context (2017) Birchenough S.N.R., Williamson, P. and Turley C. Futures of the Sea: Ocean Acidification *https://www.gov.uk/government/publications/future-of-the-sea-ocean-acidification*).

related to the phytoplankton growth in spring and late summer, the respiration of fauna and the breakdown of the produced organic matter subsequently[6]. Similar effects have been noted in many parts of the world (Carstensen et al., Sutton et al., 2016). These cycles operate alongside the background trend of slow overall acidification. The relationship between this short-term variation and the long-term trends can be considered as analogous to weather and climate changes in the atmosphere and it is essential to monitor both scales of variability in order to understand their effects on marine ecosystems.

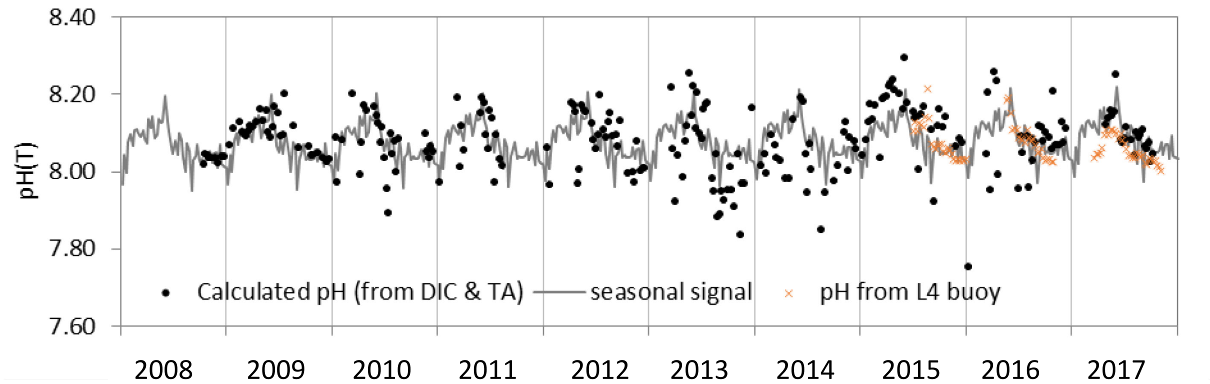

Figure 2: Annual pH cycle at the Western Channel Observatory L4 site off Plymouth (See Kitidis et al., 2012).

Note greater seasonality and short term variability than seen in the open ocean (Figure 1) reflecting more complex biological, chemical and physical dynamics in coastal waters. The data set includes both water chemistry measurements ("calculated pH") and pH sensors ("pH from L4 buoy") showing these sensors can provide very useful data in these environments. The grey line is the average seasonal cycle. Over the ten years of this record the acidification trend is not statistically significant, although there is a decline in dissolved inorganic carbon (not shown). Image courtesy of Helen Findlay PML. The data collection was funded by the NERC National Capability funded Western Channel Observatory.

In addition to the measurement of short and long term trends of OA in coastal and open oceans, the pH is known to decrease systematically with water depth (Figure 3). With vulnerable habitats such as cold water corals existing in specific deep, cold water locations, it is important for conservation strategies to understand the variations in pH in both surface waters and at depth.

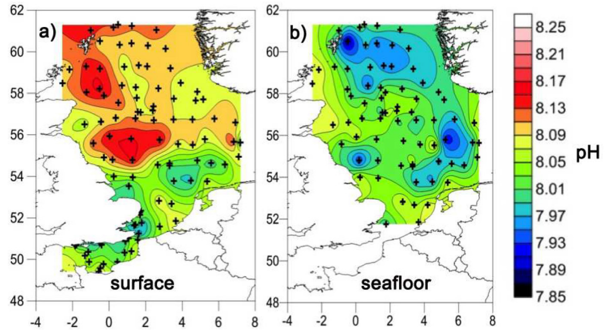

Figure 3: pH in surface and bottom waters in the North Sea, July-August 2011 indicating that in the more northern stratified water, pH in the deeper waters is typically ~0.2 units lower and hence the need to monitor throughout the water column in such regions. From Greenwood & Pearce, in MCCIP, 2013. http://www.mccip.org.uk/media/1252/2013arc_sciencereview_05_ocac_final.pdf

Measuring any of the components of the marine carbon chemistry system, at sufficient accuracy and precision to document the long-term changes in pH, is challenging and requires specialist equipment and skilled analysts. The requirements for data to define long term trends ("pH climate") are somewhat different from the short-term trends ("pH weather") with the latter requiring higher frequency sampling but with somewhat less sensitivity.

The UK Ocean Acidification (UKOA) research programme ran from 2010 to 2015, jointly funded by National Environment Research Council (NERC), Defra and the Department for Energy and Climate Change (DECC). This internationally significant project resulted in: (1) a greatly improved scientific understanding of the scale and impacts of OA at a global and UK scale; (2) the development of considerable OA research expertise in the UK; and (3) the establishment of a time series of OA measurements in UK waters.

Since the conclusion of the UKOA programme, relevant UK research in this area has continued, funded by Defra (the PLACID programme[8]), by NERC (through smaller scale research grants and national capability research), jointly (through the Shelf Sea Biogeochemistry programme, SSB[9]) and *via* several programmes related to potential carbon capture and storage.

Research worldwide has also developed rapidly over recent years (Riebesell and Gattuso, 2015), and recognising the need for sustained and coordinated monitoring effort, the international scientific community has developed the Global Ocean Acidification Observing Network (GOA-ON)[10] with support from various UN agencies, the US National Oceanic and Atmospheric Administration (NOAA) and (initially) from the UKOA research programme. The GOA-ON initiative has drawn together scientific consensus from around the world to collate OA monitoring information, develop protocols for such monitoring, and hold training workshops in regions currently lacking relevant research capacity and capabilities. Existing or anticipated monitoring activity within the GOA-ON network is shown in Figure 4.

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[8] Placing Ocean Acidification in Wider Fisheries Context (2017) Birchenough S.N.R., Williamson, P. and Turley C. Futures of the Sea: Ocean Acidification *https://www.gov.uk/government/publications/future-of-the-sea-ocean-acidification*).

[9] https://www.uk-ssb.org/

[10] (http://www.goa-on.org/documents/resources/GOA-ON_2nd_edition_final.pdf)

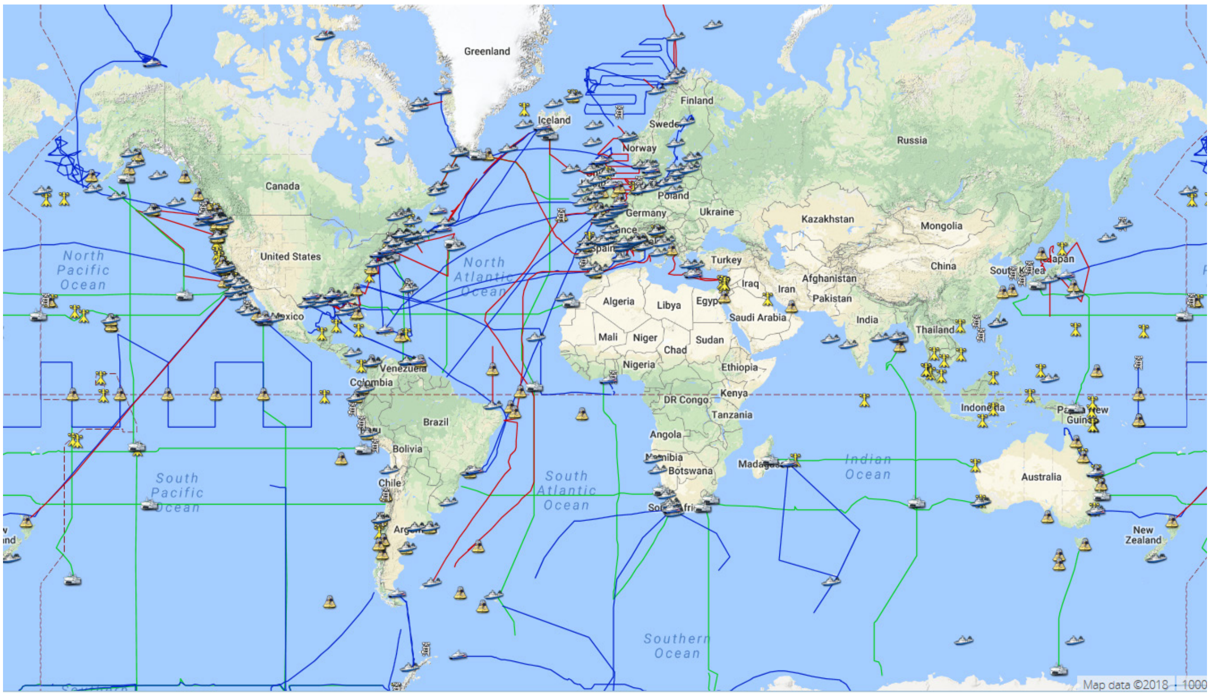

Figure 4: Map of current Global Ocean Acidification Observing Network (GOA-ON) components, showing proposed, regular ship cruises with potential mooring and water sampling time-series stations, indicated as buoys (Download from: *http://portal.goa-on.org/Explorer* Feb 2018).

1.4 Monitoring ocean acidification to understand its impacts

OA is now clearly evident *via* measurements from several open ocean time-series stations (Bates et al., 2014) (Figure 1), a trend consistent with model simulations of our understanding of the marine carbon cycle (Orr et al., 2005). Future projections of OA based on these models are that by 2100, under emission reductions currently committed under the Paris Agreement, average surface ocean pH will decrease by 0.2-0.3 units compared to pre-industrial levels (Orr et al., 2005), or by ~0.4 units if there is no mitigation effort.

This acidification is likely to have a major impact on marine ecosystems, although it is currently difficult to predict with any confidence the full range and nature of this impact. The impact is likely to be particularly serious for organisms that make their shells and external structures from calcium carbonate as these organisms will need to expend greater energy to create these calcium carbonate structures (Sunday et al., 2017). There has been extensive recent research to investigate the impacts of ocean acidification and to try and understand the capacity of organisms to adapt to the challenge of ocean acidification. We now know that marine organisms are exposed to a naturally variable pH environment although this has not usually been allowed for in many experimental studies to date.

Furthermore, the seasonal pH cycle itself is also changing as a result of CO_2 emissions (Landschutzer et al., 2018), and depth-related changes of pH (of >0.2 units) can develop in seasonally-stratified waters. Whilst it is not yet clear whether the greater impact of OA on organisms will be driven by the average or seasonal extremes of the pH cycle, the latter could be important for larval or juvenile stages of the life cycle, that are generally more sensitive than the adult stages.

The UK needs a monitoring programme to understand the scale of challenge faced by its marine environments from ocean acidification. This monitoring of OA in UK waters needs to be at sufficient spatial and temporal density to capture the key features of the pH system, whilst being logistically and financially reasonable. Monitoring sites also need to be representative of the broad classes of marine environments of interest (i.e. in the different water depths, hydrodynamic regimes and ecosystems occurring in UK waters). This sampling can be complemented by using sensors that are now able to provide information on the seasonal cycling of pH in coastal waters, and the *in situ* conditions experienced by organisms on the seafloor and in the water column, not just at the sea surface.

Computer models can be used to project the acidification trends at open-ocean, shelf sea and coastal sites into the future (forecast) and look back (hindcast) in time, taking account of changes in the relative importance of global, regional and local factors (and hence increasing complexity) for these (Artioli et al., 2014). Whilst forecasts are useful to inform management and policy decisions going into the future, hindcasts may prove useful in reconstructing pH baselines for areas currently lacking sufficient time-series data. These models also offer a means to consider the impacts of multiple stressors and global change pressures on the marine environment and to scale up individual site data to the wider area. Modelling therefore needs to be seen as an important part of the overall strategy to monitor OA. However, the models require robust and comprehensive validation using data from routine monitoring of OA at a range of sites. Without the validation, models cannot reliably quantify the development of OA and its response to anticipated changes in both atmospheric CO_2 and regional/local environmental variables (river flow, stratification etc.) under different emission scenarios.

In summary, there is clear evidence of OA taking place and a strong likelihood that this will have detrimental effects on marine ecosystems. This acidification will occur alongside other environmental stresses, and effective policy responses will need to be underpinned by a monitoring programme to understand how the pressure from acidification is developing. The UK has considerable expertise in OA research, modelling and monitoring, with strong links to the relevant global activities and is therefore in a strong position to be a global leader in this field.

2. Monitoring ocean acidification: recommendations for approaches and techniques

In order to meet the challenges of monitoring OA, there has been considerable effort in the marine science research community to develop suitable automatic *in situ* sensors to measure pH and associated ocean parameters. Such sensors can already provide 'pH weather' data suitable for biological monitoring (Sunday et al., 2017), and in investigating the causes of pH variability. They can also be used on Argo floats, sampling throughout the open ocean water column for several years with a pH accuracy of ~0.005 (Johnson et al., 2017, Russell, 2018). The UK has strengths in this area, particularly at the National Oceanographic Centre, Southampton[11]. These initiatives are expected to provide the most cost-effective route for future routine measurements of OA in UK territorial waters and UKOTs in the long term. There is the potential for the UK to become a world leader in this area of sensor development, given appropriate and sustained support.

Nevertheless, the collection and laboratory analyses of water samples are still currently needed for 'pH climate' data, to provide the accuracy and precision for determination of long-term trends in OA. Whilst we expect increasing use of *in situ* sensors over the next five to ten years, routine water sample monitoring will still be required to calibrate and validate the sensors, and to ensure long-term comparability and high-quality accuracy. Such ground-truthing of data is required because of problems of instrumental drift and sensitivity changes, as well as issues of biofouling of the equipment by algae, microbes or animals.

We fully endorse the GOA-ON recommendation[12] of the following minimum determinants for time-series OA monitoring in addition to carbonate system parameters: temperature, nutrients, salinity, pressure (water depth), dissolved oxygen, fluorescence (providing an estimate of phytoplankton chlorophyll and biomass) and irradiance. It is important to note that the additional costs of collecting this information are modest while there are substantial gains in terms of understanding the process of OA and its impacts.

Laboratory analysis of marine carbonate chemistry requires specialist equipment and skills. The UK has several laboratories with this capacity in government agencies, research centres and universities. In addition, during the UKOA programme there was an operational central analysis facility for OA. Whilst this laboratory still exists and operates on an ad-hoc basis, financial support ceased when the UKOA programme finished. We believe it is necessary that a centralised facility and/or facilities are in place for analytical work, training and standardisation of results as part of a high-quality, coordinated UK OA monitoring. This facility could be delivered by a partnership between the experienced groups in the UK.

[11] http://noc.ac.uk/technology/technology-development/instruments-sensors

[12] http://goa-on.org/about/plan.php

We also recommend that the UK commit resources to allow its scientists to become influential and active participants in the GOA-ON network programme.

Recommendation 1: **The UK should make further investment in sensor development for ocean acidification monitoring.** Such work should build on existing R&D work in developing automatic methods and technologies for carbonate chemistry measurements; it should also promote the worldwide commercial exploitation of such innovations, through both UKRI and government support.

Recommendation 2: **UK ocean acidification monitoring should follow international quality standards, based on a suite of core physico-chemical measurements and preferably in the context of additional ecological information.** Most time series should be based on discrete water samples, analysed for at least two of the four core carbonate chemistry variables (pH, pCO_2, DIC and TA) as well as temperature, salinity, oxygen and nutrients. Such monitoring should, where feasible, also involve or be aligned with the collection of information on other important biogeochemical and ecological variables such as bio-optical parameters, chlorophyll, and pelagic and benthic community composition.

Recommendation 3: **A nationally-funded facility for quality-controlled carbonate chemistry analyses should be established**, based on one or more centres of excellence and wider networking. This facility will use accepted international standard reference materials, carry out inter-calibration exercises, and provide national and international training.

Recommendation 4**: UK ocean acidification monitoring data should be suitably archived and made freely and rapidly available to other users**. Data should be collected and archived in line with the Marine Data Information Network (MEDIN) principles in a UK data archive centre and made available via the data portal of the Global Ocean Acidification Observing Network (GOA-ON). Regular reporting of data syntheses is encouraged; e.g. through the Marine Climate Change Impacts Partnership (MCCIP) [13].

Recommendation 5: **National support should be made available to assist scientific involvement in the GOA-ON initiative**. This should include attendance at international meetings and support for hosting the regional GOA-ON hub for the North East Atlantic and Europe.

[13] (http://www.mccip.org.uk/)

3. Recommendations for monitoring of ocean acidification in UK Territorial Waters and the adjacent North East Atlantic

3.1 Current site-based OA monitoring in UK Territorial Waters

The report considers here UK coastal and shelf sea waters, also the adjacent open ocean region, noting that the latter mix with and therefore can profoundly influence, the former.

The anticipated rate of change in OA means that such change can only be accurately detected over many years. A long-term commitment to OA monitoring and assessment is therefore essential to ensure the collection of the evidence required to support policy needs and management. This needs to be done in conjunction with on-going measurement of atmospheric CO_2 concentration.

There are two well established time-series in UK waters: (1) Stonehaven ecosystem monitoring site off the North-East Scottish coast (León et al., 2018); and, (2) the Western Channel Observatory (WCO) in the English Channel off Plymouth (Kitidis et al., 2012). Measurements have been made at these sites of the marine carbonate system, and hence ocean acidity, for approximately seven years (Stonehaven) and 10 years (WCO), alongside other relevant marine water quality measurements. In addition, Cefas has made time-series measurements at the two North Sea Smartbuoys[14] located in very different marine environments- Warp (outer Thames) and West Gabbard, for 3 years between 2010 and 2013, funded by UKOA. These four sites have all provided relatively high temporal resolution (monthly or more frequent sampling).

The UK is fortunate to have several well established marine environmental monitoring sites which have now also developed records of ocean acidification. Although established principally for other marine environmental monitoring objectives and located with reference to cost and accessibility, these OA monitoring sites provide an appropriate basic network of sampling sites to characterise the pH and marine carbonate chemistry conditions prevailing on the UK shelf. They stretch from the south to the north and include waters that seasonally stratify[15] in the English Channel, while at the other stations the sea water is vertically well mixed throughout the year. All the sites are influenced to some extent by river outflows but the character of those rivers, particularly in terms of the carbonate system and nutrient loadings, are very different. We therefore recommend that these

[14] Smartbouys highly instrumented buoys with water sampling capability operated by CEFAS https://www.cefas.co.uk/cefas-data-hub/smartbuoys//instruments-sensors

[15] Stratification: separation of the deep water from the surface layers in the summer time due to warming, restricting air-sea exchange and resulting in some degree of seasonal oxygen depletion, nutrient build up and acidification in deeper waters.

existing monitoring sites become the core of the UK's long term OA monitoring programme.

Recommendation 6: **The existing four UK time series for ocean acidification should be maintained, on a long-term basis**. These sites comprise the Western Channel Observatory, Stonehaven and two North Sea SmartBuoys. The frequency of direct sampling at the SmartBuoys should be increased from quarterly to monthly.

3.2 Additional sites for a UK OA monitoring network

The existing sites discussed above, do not cover all of the main types of marine waters on the UK shelf. The SAC sub group therefore considered what additional sampling would be appropriate to allow a more comprehensive understanding of OA in UK waters.

Nearshore regions, within a few kilometres of the coast, are likely to be the most variable for pH and many other parameters, reflecting variability in impacts of river inputs, in particular. These near-coastal areas are also particularly important for shellfish harvest and aquaculture. The SAC sub group agreed that regular monitoring of OA in all such habitats and sites of interest was currently unrealistic; nevertheless, the identification of sites of particular commercial or other societal interests would allow the future monitoring of at least some of those sites to be developed, for example in partnership between the commercial companies and relevant agencies.

Marine Scotland are adding the determination of OA parameters to its ecosystem monitoring site in Loch Ewe which should serve as a suitable general monitoring site for a range of Scottish sea lochs that are widely used for aquaculture.

The current observation network does not provide a sampling site in the northern UK waters subject to seasonal stratification. In seasonally stratified waters, the decomposition of organic matter in deep water leads to a natural lowering of pH during summer as is seen in the North Sea (Figure 3). This natural lowering of pH will be exacerbated by OA and will create areas of particularly low pH, with model-projected undersaturation of carbonate. The SAC sub group identified the value in including sampling sites in waters that stratify seasonally in these regions, because of the impact of such stratification on pH and carbonate chemistry. Suitable sites for such monitoring could be in the Northern North Sea (North Dogger area where CEFAS have previously had a monitoring site), or additional support for more frequent monitoring of existing sampling sites in the Irish Sea.

This proposed network of sampling sites on the UK shelf is shown in Figure 5.

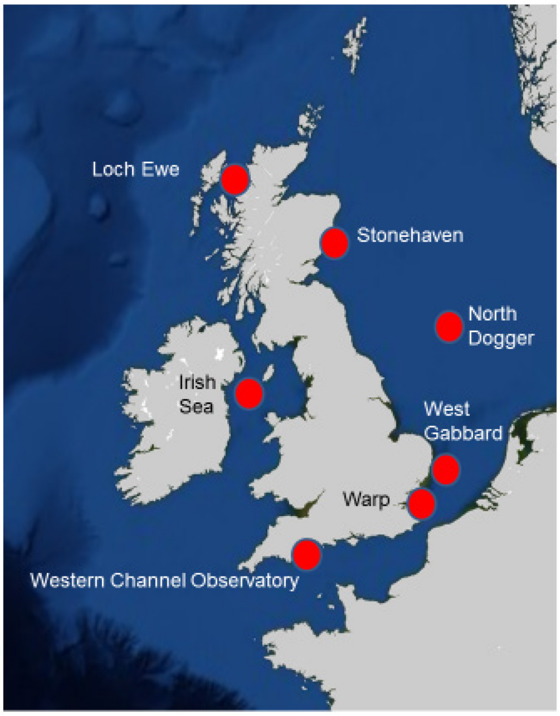

Figure 5: Map showing proposed OA monitoring network on the UK shelf

> ***Recommendation 7:*** **Additional UK sites for ocean acidification monitoring should be established, to cover other important habitats.** In addition to the Loch Ewe site, currently being established by Marine Scotland, fixed sampling sites (covering the full water depth) should be considered in seasonally-stratified areas such as the northern North Sea or the Irish Sea.

Seafloor habitats at the shelf-edge are experiencing changes in carbonate chemistry conditions with major ecological implications. In particular, the distribution and abundance of cold-water corals are expected to be negatively impacted by reductions in pH and carbonate saturation state. In addition, OA-induced changes in primary production and phytoplankton species composition could affect the feeding grounds and nursery areas of many commercially-important fish species. High frequency sampling in these regions by research ships is unrealistic, but annual visits (see below) coupled with using ships-of-opportunity and *in situ* automated technologies should be considered for future OA monitoring at the shelf-edge. The case for such an automated sampler in these regions and the appropriate location for such sampling should arise from the results of existing research activity e.g. the SSB programme[16].

[16] https://www.uk-ssb.org/

In terms of UK shelf waters, the sub group believe that this expanded network of sampling sites, proposed in Recommendation 7, would be sufficient to characterise the broad types of environmental systems. Sampling for carbonate system parameters on cruises between sites and possibly on commercial vessels offers an opportunity to consider further spatial variation. In the future the network of sampling sites will evolve in response to developing technological capability of relevant sensors. Modelling of OA parameters (Artioli et al., 2014) will allow the integration and extrapolation of the data from these monitoring sites to project the overall conditions across the UK shelf with some confidence, and this would include the UK's network of marine protected areas.

At several of the OA monitoring sites discussed above, there are existing sampling buoys of various types. These sites may be able to offer an excellent platform for testing new sensors and even remote sensing algorithms for OA as they are developed.

3.3 Incorporating OA monitoring into existing UK long-term marine observation activities

The waters of the UK shelf are heavily influenced by exchange with waters in the adjacent North Atlantic and hence understanding OA trends in these waters is valuable. It is not currently realistic to consider high temporal resolution observations based on water sampling of these offshore waters on the scale described above for near shore waters. However, there are some sampling and analysis initiatives that could be done by utilising existing cruises and surveys particularly those aimed at delivering time-series measurements for other ocean variables in well monitored areas. The additional costs of collecting and analysing the relevant samples on these cruises is modest following the establishment of the national facility recommended earlier.

The proposals below build on existing monitoring sites and transects, with additional opportunities highlighted that would extend UK OA monitoring into the North Atlantic Ocean and beyond. The location of some of these sites is illustrated in Figure 6.

i. The NERC supported Porcupine Abyssal Plain (PAP) site in the NE Atlantic Ocean (Hartman et al., 2015) is a site for internationally important time-series of water column measurements. This would be an appropriate site to establish a long-term sampling site for OA from the sea surface to the sea bed using sensor-based measurements, with annual water-sampling for calibration/validation.

ii. The NERC-funded Ellett Line operated by SAMS and NOC, samples between Scotland and Iceland covering one of the main connecting flows between the Arctic and the Atlantic. It is sampled annually as a hydrographic section, and has previously included marine carbonate parameters (Humphreys et al., 2016). It would be straightforward to include routine sampling for OA parameters at selected sites on the Ellett Line once per year and thereby provide monitoring of OA into this under-sampled region connecting to the Arctic Ocean. In addition, Marine Scotland go to the Faroe-Shetland Channel three times a year and could incorporate marine carbonate parameters in these visits, to provide higher frequency of sampling. In either case, sampling should extend to full depth, with consideration given to associated deployment of biogeochemical Argo floats (Russell, 2018). This full depth sampling is important in order to monitor the environment of deep-water coral communities that are ecologically important and vulnerable to acidification, along the North-West continental shelf of the UK and northern Europe (Perez et al., 2018). It may also be possible to establish additional monitoring sites off North-West Scotland in partnership with the oil industry who have platforms in these waters and elsewhere: the group encourages exploration of this option[17].

iii. The SAC sub group noted that the Sir Alister Hardy Foundation for Ocean Science (SAHFOS) is currently developing pCO_2 sensors and water samplers[18] for the continuous plankton recorder (CPR), to be trialled on North Atlantic routes. This initiative would complement and extend the existing use of ships of opportunity for underway measurements of pCO_2 currently coordinated through the international Surface Ocean CO_2 Atlas (SOCAT) initiative, with strong UK involvement (e.g. > 20 years sampling of the UK-Caribbean route (Watson et al., 2009)). The additional use of CPRs will extend the range of routes, whilst also providing information on plankton populations that are likely to affect, and be affected, by ocean acidification.

iv. The SAC sub group also notes that the Arctic region is one of significant environmental change as a result of global warming and also a region where the UK has considerable commercial and environmental interests. Consideration of the Arctic is arguably outside the terms of reference of the group, but the importance of monitoring OA in this complex, dynamic and rapidly changing region was noted. The NERC Arctic research programme[19] will offer a mechanism to develop expertise in this region and evaluate monitoring options alongside the UK collaborations with other Contracting Parties to OSPAR, including Iceland, Denmark and Norway. It is worth noting that French scientists currently run a nearshore OA monitoring station in Ny Alesund on Svalbard.

There are also options for the UK to make a globally-significant contribution to OA monitoring in waters well beyond the NE Atlantic Ocean.

The NERC-supported Atlantic Meridional Transect (AMT)[20] sampling programme collects detailed oceanographic measurements once a year, and could sample twice, between the

[17] The SAC sub group is aware of successful cooperation between scientists and the offshore industry to enable sampling from their platforms in the UK and more widely. For example, the University of Edinburgh recently completed a trial that successfully collected water samples with BP during their routine operations in the northern North Sea, in the Mediterranean off Libya and in the South Atlantic Ocean off Angola

[18] https://www.sahfos.ac.uk/about-us/news-events/plymouth-marine-science-centres-scoop-14-million-in-funding-awards/

[19] http://www.nerc.ac.uk/research/funded/programmes/arctic/

[20] http://www.amt-uk.org/

UK and the Southern Ocean. This is a globally important programme that has produced important new basin scale understanding of oceanographic processes. This programme has previously measured OA parameters and has published a 18 year time series of surface ocean carbon dioxide measurements (Kitidis et al., 2017). With additional funding, the AMT could: i) conduct transect-based sampling and return stored samples to the UK for measurement to address long term large scale changes in OA, i.e. “pH climate”; and ii) deploy 5-10 biogeochemical Argo floats (Russell, 2018) per transect, to obtain similar full-depth information throughout the year and over a very much larger area, to determine spatial and temporal variability, i.e. “pH weather”. Together these two approaches would provide a basin wide picture of the evolution of OA not available by other sources, including the South Atlantic Ocean which has not been well-sampled to date. With minor re-routing, the AMT cruise track could pass through the Exclusive Economic Zones (EEZs) of at least four UKOTs in the South Atlantic Ocean (Ascension, Saint Helena, Tristan da Cunha and Falklands), discussed in section 3. It could also be extended to include the Drake Passage transect from the Falkland Islands to the Antarctic Peninsula (Meredith et al., 2011), and thereby along with the Ellett line, achieve near-pole to pole coverage from at least 60^{0}N to 60^{0}S. The delivery of OA data and evidence from this initiative could be seen within 2-3 years, and could build on an existing time-series programme at modest extra cost; however, to be meaningful in the long-term would require foresight and secured long-term funding.

The UK has had strong involvement in the Argo float programme since it began in around 2000, largely in terms of measuring physical oceanography parameters. UK researchers have also been involved in test deployments of the new biogeochemical floats (with a global total of ~200 already deployed, with US NSF support; Russell, 2018). Whilst site-specific measurements and calibrations will still be needed, the UK now has a unique opportunity to benefit from this much more comprehensive and informative approach, obtaining novel data of global importance.

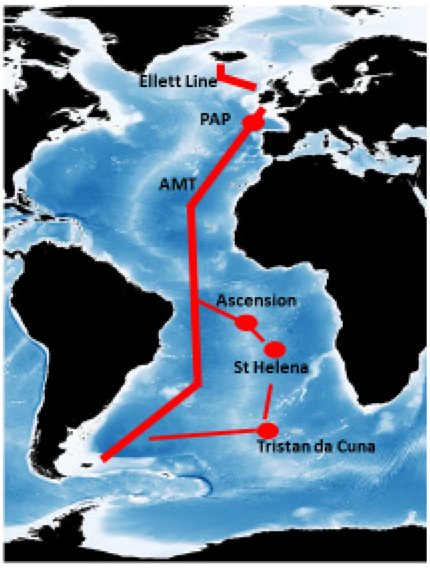

Figure 6 showing sites of AMT and Ellett line transects and PAP monitoring site. Thin red line indicates possibility of rerouting AMT to visit the waters of Ascension, St Helena and Tristan da Cuna. Background image reproduced from the GEBCO world map 2014, www.gebco.net

> ***Recommendation 8:*** **The spatial coverage of ocean acidification observations should be further increased by using new technologies to link with other marine monitoring activities in UK waters and more widely**. Cost-effective opportunities exist to include routine ocean acidification monitoring in the sampling undertaken along the Ellet line, in the Faroe-Scotland Channel, along the Atlantic Meridional Transect (AMT), by Continuous Plankton Recorders (CPRs), at the Porcupine Abyssal Plain (PAP) site in the North Atlantic, and by the deployment of instrumented Argo floats.

4. OA monitoring in UK Overseas Territories

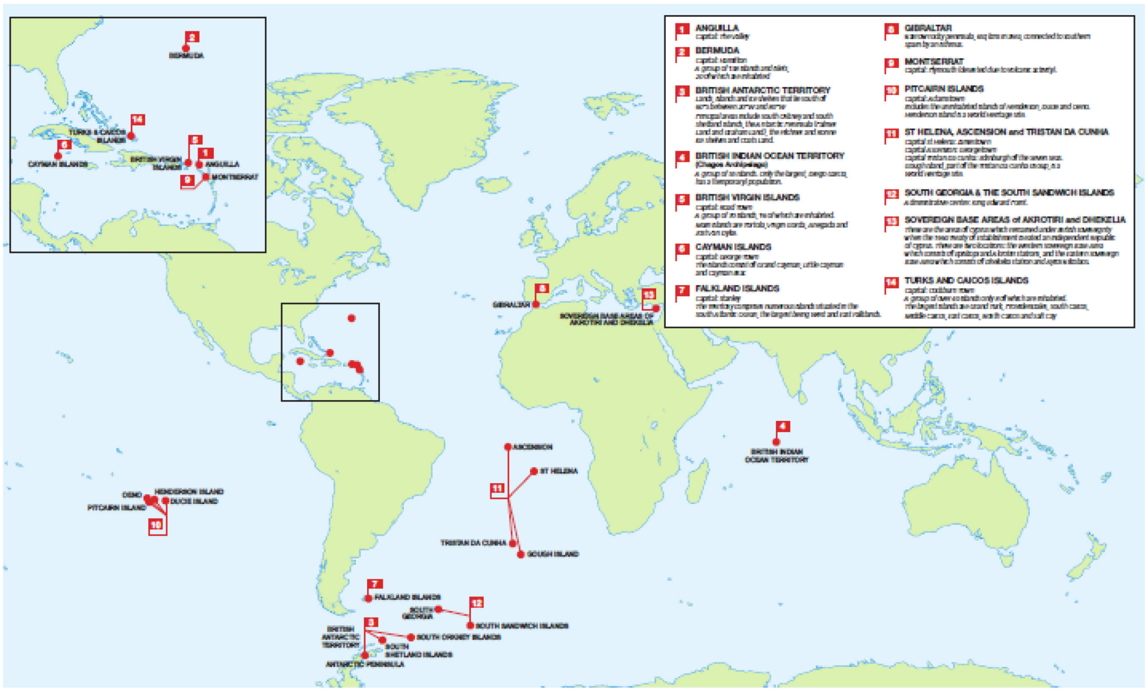

Figure 7: Map to show UK Overseas Territories and regions of the Antarctic where the UK has research activities. From The UK Overseas Territories; Security, Success and Sustainability, Foreign Commonwealth Office *https://assets.publishing.service.gov.uk/government/uploads/system/uploads/attachment_data/file/14929/ot-wp-0612.pdf)*

4.1 OA monitoring initiatives in UK Overseas Territories

The SAC sub group was tasked with providing options for monitoring OA within the marine waters of UKOTs. This work is complementary to the UK government commitment set out in the Blue Belt programme[21] to undertake fisheries assessments, habitat mapping and knowledge transfer activities. Furthermore, by using the proposed network of laboratories and data management, outlined above, to support OA sampling in UKOTs, the sub group believes the UK can facilitate data analyses and contribute to wider understanding of OA impacts on ecosystems and communities in UKOTs and comparable marine systems.

The SAC sub group discussed possible locations for OA monitoring in UKOTs with three primary criteria in mind:

1. The benefits that sampling in these territories might offer in terms of providing OA data in regions of the world poorly served by ongoing GOA-ON activities (**see** Figure 4).

2. Whether there were likely threats from OA to important ecosystems and economies, particularly in the context of coral reefs, fisheries and/or the marine protected areas that have been declared around many of these territories.

3. Practical and logistic issues in terms of local scientific capacity as well as sampling capability and sample transport. Several UKOTs have very small resident populations and establishing advanced analytical capability for OA measurements is probably unrealistic. Transporting samples would currently involve secure transport of glass sample bottles containing a potentially hazardous preservative and would require specialist transport considerations. Samples could then be analysed at the UK analytical facility proposed above (**Section 2, Recommendation 3**). Under such conditions, long-deployment sensors would be a cost-effective alternative for initial work, providing that necessary calibration/validation can be carried out (at least annually).

4.2 Potential/existing OA monitoring in UKOTs

In the context of these considerations, the sub group considered the potential to monitor OA in the following UKOTs.

Bermuda. One of the most important ocean time series sites, with an excellent record of OA monitoring over 30 years (Figure 1), is situated off and run from the UK Overseas Territory of Bermuda and is funded by Bermudian and US sources (Bates et al., 2014). The SAC sub group consider that this monitoring has great value by providing one of the

21 (https://www.gov.uk/government/uploads/system/uploads/attachment_data/file/662392/27_OCT_Introducing_Blue_Belt_FINAL-_updated1.pdf)

main long term ocean monitoring sites for OA and other biogeochemical parameters and strongly supported its continuation.

British Antarctic Territories[22]. Monitoring activities for OA in the South Atlantic/Southern Ocean region are currently limited, particularly for year-round monitoring activities. These environments are associated with major marine protected areas. Furthermore, polar regions are particularly vulnerable to carbonate under-saturation ($CaCO_3$ dissolution) because of increased solubility of CO_2 at low temperatures, as well as being regions of rapid environmental change due to global warming (Clarke et al., 2007). In addition, pteropods (pelagic calcifying molluscs) form an important part of the plankton ecosystem and they make their shell from the more soluble form of calcium carbonate- aragonite. Shell damage is already occurring in some regions, with high risk to the future viability of pteropod populations in these Southern Ocean waters by 2050 (Orr et al., 2005). Hence the sub group considers that monitoring of OA in this region has high priority, and the infrastructure provided by the British Antarctic Survey (BAS) makes such monitoring realistic.

There has been some ongoing monitoring of OA at the time series site off the BAS Rothera base (Legge et al., 2017). The former could easily be converted into a long-term monitoring site for OA using the existing BAS routine sampling capability with samples shipped by sea back to the UK OA facility for analysis annually. A similar sampling programme could be established at South Georgia. It would also be possible to strengthen existing monitoring in the Southern Ocean offshore of South Georgia (Scotia Sea Open-Ocean Biological laboratories (SCOOBIES)[23] with additional water sampling for OA. This would provide data from a different Southern Ocean region utilising existing infrastructure at the South Georgia station and sample shipment arranged by BAS.

The Falkland Islands could provide a third sampling site in this region. However, the SAC sub group found the case for developing monitoring near the Falklands to be relatively lower priority in terms of the limited OA-vulnerable habitats in the region (subject to our current understanding).

British Indian Ocean Territory (BIOT/Chagos). BIOT includes a major marine protected area and large areas of coral reefs. There has been minimal impact by human activity on these reefs, however, they are vulnerable to a range of environmental pressures, particularly coral bleaching, alongside OA. The SAC sub group therefore considers that BIOT represents a high priority in terms of monitoring environmental threats in a vulnerable environment. Routine water sampling (at Diego Garcia) in liaison with the UK marine conservation officer, could be possible: this option warrants further investigation. There are also annual international scientific expeditions to BIOT, funded by the Fondation Bertarelli (www.fondation-bertarelli.org/marine/chagos). Through such support, a US-UK collaboration, led by Robert Dunbar, Stanford University, has already initiated sensor-based OA monitoring at BIOT. The SAC sub group recommends that these existing efforts

[22] https://www.gov.uk/world/organisations/british-antarctic-territory
[23] https://www.bas.ac.uk/project/scoobies/

should be strengthened, to develop a long-term, high quality, time series for OA monitoring in this important, yet under-sampled, ocean region.

The Pitcairn Islands are an archipelago of exceptionally remote islands in the southern Pacific Ocean, with a very small population and one of the world's largest fully protected marine reserves, formally declared in 2016 by the UK. The island is visited at least annually by scientific expeditions and its EEZ contains marine habitats of major conservation value, including coral reefs. This is therefore a region where OA monitoring is a priority, particularly given the limited routine sampling that is going on under GOA-ON in the tropical south east Pacific. The logistics of shipping samples are likely to be challenging and should be investigated further given the priority to gather OA data from this region. As at BIOT, it would seem to be a region where it would be appropriate to deploy automatic OA monitoring devices accompanied by monthly-to-annual water sampling for calibration.

St. Helena, Tristan da Cunha and Ascension Island. These small islands (Figure 6) are in regions of the South Atlantic Ocean where there is currently very little information on OA conditions. The islands have valuable fisheries (crawfish on Tristan da Cunha and tuna on St. Helena) that might be vulnerable to OA. The species of primary conservation value on Ascension (turtles) seem unlikely to be directly vulnerable to acidification. Thus OA monitoring (although more practicable) is of lower priority for this island.

These islands are remote and the UK has established a sustainable use MPA[24] around St Tristan da Cunha and St Helena with aims of declaring an MPA around Ascension by 2019. Transport of samples off the islands could be challenging. The large military transport operation on Ascension offers easier transport options however, supply ships to the islands probably provide the best arrangements for St Helena and Tristan da Cunha, possibly with linkage to minor re-routing of the AMT transect. As above, these sites should be considered for early deployment of new automatic monitoring systems, coupled with a reduced water sampling programme to provide calibration.

Caribbean Territories (Anguilla, Cayman, Monserrat, British Virgin Islands, Turks and Caicos). All of these areas contain important and OA vulnerable habitats such as coral reefs, and have economies that are highly dependent on the marine environment. Currently, the Caribbean region is relatively-well monitored for OA via initiatives from the USA National Ocean and Atmospheric Administration (NOAA) (Figure 4). An annual transect from Bermuda to Puerto Rico (operated as part of the BERMUDA BATS program see above) also provides sampling in this region. Overall, the sub group believes these islands to be of somewhat lower priority than the sites identified above, in terms of trying to understand large scale OA patterns, because of existing monitoring in the region. However, due to economic reliance and the high ecological value of the marine environment in the region, (including Belize where there is already Cefas partnered work on OA) improved OA and ecological monitoring in their near shore waters in these regions

[24] A sustainable use MPA is an area set aside for marine ecosystem protection that allows carefully managed activities, such as fishing and tourism.

may be a priority for these countries and would be relatively easy to set up. Cefas is conducting additional work in Belize by collecting marine carbonate chemistry samples to set baselines for OA and fisheries in Belize as part of the Commonwealth Marine Economies Programme and this could form a template for such activities as discussed below for the Commonwealth countries more generally (see **Section 4**). Given the existing infrastructure and skills in OA monitoring in the Caribbean, use of an established OA laboratory facility (as recommended above) could provide straightforward and robust means to develop partnership working and knowledge exchange between the UK, the Caribbean UKOTs and the wider region. The establishment of OA monitoring in these islands should be considered collaboratively between the UK government and these countries.

Mediterranean (Akrotiri and Dhekelia in Cyprus and Gibraltar) There is extensive OA monitoring in the Mediterranean conducted by countries other than the UK and so the sub group concluded there is no need to develop additional OA monitoring around these territories.

Recommendation 9: **Existing ocean acidification monitoring initiatives in UK Overseas Territories (UKOTs) should be supported, and further consideration given to the establishment of additional sites**. In addition to strengthened links with well-established OA monitoring at Bermuda, opportunities exist for knowledge exchange in other UKOTs (e.g. in Caribbean) through training of support staff, provision of standards, inter-calibration exercises, and use of UK analytic facilities. Based on existing evidence we suggest the first priority is to extend, and improve the value of, current OA observations in the British Antarctic Territories and the British Indian Ocean Territory (BIOT), and for new sites to be established in Pitcairn, St Helena and Tristan da Cunha.

5. Support for ocean acidification monitoring in Commonwealth Countries

Many countries around the world, including those within the Commonwealth, have interests in developing OA monitoring to manage human activities impacting their marine waters and already contribute to the GOA-ON network. The SAC sub group has identified scientists in 28 Commonwealth countries who are associated with GOA-ON (Figure 8).

In addition to the potential to collaborate more directly with OA programmes in countries such as Belize (see Section 4.2), there are relevant initiatives and activities that offer great scope for the UK to work more closely with Commonwealth countries that have major expertise in OA sciences. GOA-ON affiliated scientists have recently organised OA training workshops for climate change specialists in Commonwealth countries such as Tanzania and Fiji, with support drawn from the Commonwealth Marine Economies project for the event in Fiji last year. By working with countries such as the US, Australia and Sweden who have led on these workshops, the UK can increase and improve its leadership capacity in OA monitoring and knowledge exchange. Future events to engage with could be the forthcoming GOA-ON training workshops in the Caribbean (scheduled for 2018) and India. The creation of a core OA analytical and data facility within the UK provides a centre of excellence which can provide a focus within which to offer training, knowledge exchange and support to Commonwealth countries based on their identification of how the UK can most appropriately support their needs.

Recommendation 10: The proposed UK core facilities for OA measurements, data archiving and associated infrastructure should be used to offer training, support and opportunities for knowledge exchange with Commonwealth countries interested in OA monitoring.

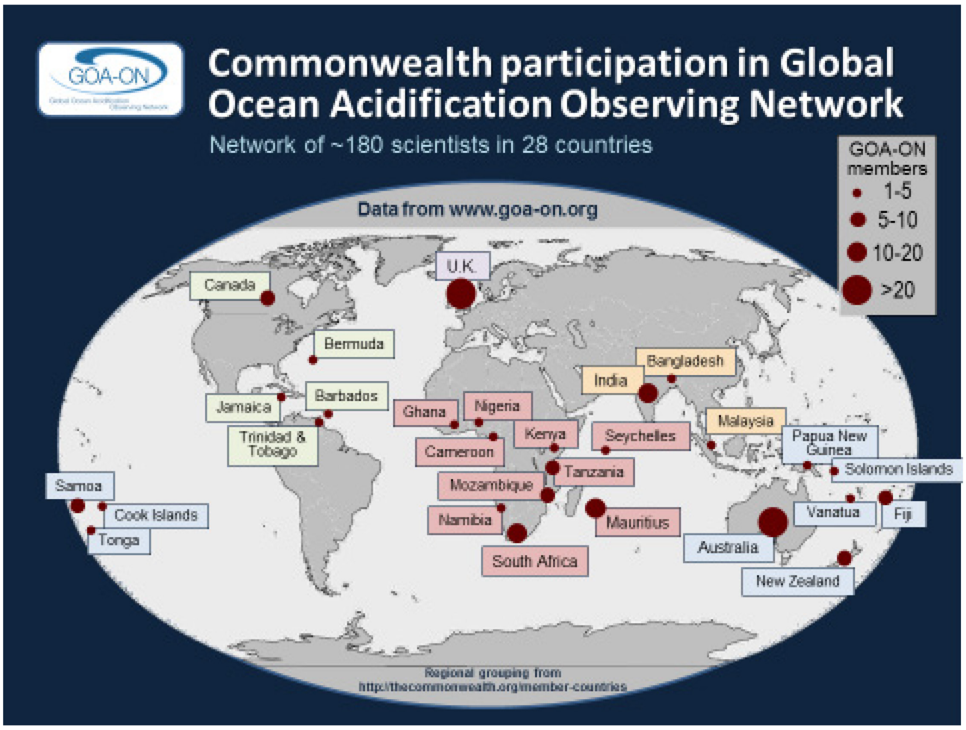

Figure 8: Map showing the Commonwealth countries with scientists associated with the GOA-ON network and the approximate numbers recorded.

6. Conclusions for UK led OA monitoring

OA represents a major long term and global scale threat to the marine environment. The UK has world leading marine science capability as well as major maritime interests and responsibilities, and therefore needs to play a prominent global role in monitoring and addressing the OA challenge. The sub group believe that the programme proposed above will allow the UK to play a leading role in worldwide OA monitoring, and also provide information required for policy makers to respond to the developing challenges of OA alongside other stresses in the marine environment. The proposals here also provide a mechanism to support capacity building for OA and wider marine science development in Commonwealth countries. The recommendations aim to provide information on OA for the UK shelf waters and for UKOTs in a timely and efficient way, establishing a monitoring programme to be maintained and developed over many years to come. The approaches recommended recognise that developing technologies will allow the sampling strategy to evolve, improve and become more cost-effective as new automated observing systems of sufficient sensitivity and reliability become available.

Further, UK commitment to the development of novel sensor technologies capable of making “pH climate” measurements will lead to a paradigm shift in capabilities to predict the development of OA throughout the world’s oceans. Development of specific technology for early warning detection in OA for vulnerable ecosystems or areas could be considered, further adding to the UK’s resilience to the impacts of OA.

The overarching opportunity is to establish world-leading facilities for OA monitoring in a highly dynamic shelf sea environment as well as in under-sampled and ecologically sensitive ocean regions. This will consolidate UK leadership in global OA networks (GOA-ON). The UK (Plymouth Marine Laboratory) is developing a GOA-ON hub for the North East Atlantic and Europe and is represented on the GOA-ON Executive Council, giving the UK an opportunity to play an international leadership role for OA monitoring and research. The sub group endorse the development of this hub and its associated leadership role and recommends the UK government formally supports it.

Appendix 1: Recommendations of the OA sub group of the Science Advisory Council

***Recommendation 1:* The UK should make further investment in sensor development for ocean acidification monitoring.** Such work should build on existing R&D work in developing automatic methods and technologies for carbonate chemistry measurements; it should also promote the worldwide commercial exploitation of such innovations, through both UKRI and government support.

***Recommendation 2:* UK ocean acidification monitoring should follow international quality standards, based on a suite of core physico-chemical measurements and preferably in the context of additional ecological information.** Most time series should be based on discrete water samples, analysed for at least two of the four core carbonate chemistry variables (pH, pCO_2, DIC and TA) as well as temperature, salinity, oxygen and nutrients. Such monitoring should, where feasible, also involve or be aligned with the collection of information on other important biogeochemical and ecological variables such as bio-optical parameters, chlorophyll, and pelagic and benthic community composition.

***Recommendation 3:* A nationally-funded facility for quality-controlled carbonate chemistry analyses should be established**, based on one or more centres of excellence and wider networking. This facility will use accepted international standard reference materials, carry out inter-calibration exercises, and provide national and international training.

***Recommendation 4*: UK ocean acidification monitoring data should be suitably archived and made freely and rapidly available to other users**. Data should be collected and archived in line with the Marine Data Information Network (MEDIN) principles in a UK data archive centre and made available via the data portal of the Global Ocean Acidification Observing Network (GOA-ON). Regular reporting of data syntheses is encouraged; e.g. through the Marine Climate Change Impacts Partnership (MCCIP) [25].

***Recommendation 5:* National support should be made available to assist scientific involvement in the GOA-ON initiative**. This should include attendance at international meetings and support for hosting the regional GOA-ON hub for the North East Atlantic and Europe.

***Recommendation 6:* The existing four UK time series for ocean acidification should be maintained, on a long-term basis**. These sites comprise the Western Channel Observatory, Stonehaven and two North Sea SmartBuoys. The frequency of direct sampling at the SmartBuoys should be increased from quarterly to monthly.

[25] (http://www.mccip.org.uk/)

Recommendation 7: **Additional UK sites for ocean acidification monitoring should be established, to cover other important habitats.** In addition to the Loch Ewe site, currently being established by Marine Scotland, fixed sampling sites (covering the full water depth) should be considered in seasonally-stratified areas such as the northern North Sea or the Irish Sea.

Recommendation 8: **The spatial coverage of ocean acidification observations should be further increased by using new technologies to link with other marine monitoring activities in UK waters and more widely**. Cost-effective opportunities exist to include routine ocean acidification monitoring in the sampling undertaken along the Ellet Line, in the Faroe-Scotland Channel, along the Atlantic Meridional Transect (AMT), by Continuous Plankton Recorders (CPRs), at the Porcupine Abyssal Plain (PAP) site in the North Atlantic, and by the deployment of instrumented Argo floats.

Recommendation 9: **Existing ocean acidification monitoring initiatives in UK Overseas Territories (UKOTs) should be supported, and further consideration given to the establishment of additional sites**. In addition to strengthened links with well-established OA monitoring at Bermuda, opportunities exist for knowledge exchange in other UKOTs (e.g. in Caribbean) through training of support staff, provision of standards, inter-calibration exercises, and use of UK analytic facilities. There is scope to extend, and improve the value of, current OA observations in the British Antarctic Territories and the British Indian Ocean Territory (BIOT), and for new sites to be established in Pitcairn, St Helena and Tristan da Cunha.

Recommendation 10: The proposed core facilities for OA analyses, data archiving and associated infrastructure should be used to offer training, support and opportunities for knowledge exchange with Commonwealth countries interested in OA monitoring.

Appendix 2: Terms of Reference: SAC Ocean Acidification Sub Group

Overarching aim

The overarching aim of the SAC Ocean Acidification (OA) sub group is to review the current monitoring and assessment programmes for OA and provide advice on where the UK can contribute to global OA monitoring.

As part of this review and gap analysis the sub group will look to summarise monitoring systems and data availability from work undertaken as part of the current UK OA programme and those designed to support delivery of reporting for OSPAR (Convention for the Protection of the Marine Environment of the North East Atlantic) and other international obligations and activities. It will provide an external perspective, and critically, will advise on how the UK could contribute to the effort to measure OA at a whole-ocean level.

Purpose of the review

The sub group will address two main points. What contribution the UK can make by:

1. Identifying and exploiting locations where long-term monitoring could take place in the UK, UK Overseas Territories and the Commonwealth.

2. Developing and supplying technology for reducing the costs of making measurements.

Any proposals should involve promotion of least-cost options and be focussed on delivering information relevant to policy development. The sub group will make recommendations in a short report covering the above two points.

Background

OA is a process resulting from the absorption of CO_2 from the atmosphere by the ocean. CO_2 is a soluble gas which dissolves easily in water where it contributes to the formation of carbonic acid.

Because many marine organisms have evolved in an environment where the pH is very stable they have low resilience to changes in pH. For example, carbonates which form the shells of animals in the sea will chemically dissolve at a critical level of acidity. There is some evidence that in some places the ocean pH is already affecting the ability of some organisms to form their shells.

Consequently, consistent and widespread monitoring to support identification in trends of OA at a global level are required. The UK has an opportunity to support this and drive data collection to support not only policy but national and internal reporting commitments.

There is already monitoring of OA and/or the commitment to monitor and reduce OA across a range of initiatives and obligations (e.g., EU Marine Strategy Framework Directive, OSPAR, Sustainable Development Goals, UN Convention on Biological Diversity and the action plan of the G7) and the UK has played a major part in the development of the SOCAT data products (*http://www.socat.info/*), a global initiative to provide high quality data for the CO_2 system.

Additionally there have been recent reviews and inquiries on OA which have considered OA monitoring (e.g. House of Commons Science and Technology Committee and Marine Climate Change Impacts Partnership).

This background will all be taken into account within this review and form the basis from which to start this work.

Membership

The group will be chaired by the SAC member Professor Tim Jickells. A small number of independent academic co-optees will provide additional expertise, these members are listed in Annex 1. Co-optees are not recruited through open competition but are appointed based on their specific skills and experience. The SAC OA co-optees act independently of any of their other interests.

The SAC OA sub group will be supported by Defra officials in particular, Head of Defra's Marine and Fisheries Science and Evidence Team, Marine Science Team and the SAC secretariat.

Outputs

A review report and recommendations will be agreed by the SAC and presented to Defra's Chief Scientific Advisor (CSA). The group will deliver this report to the CSA ahead of the Commonwealth Heads of Government Meeting in April 2018.

Duration of sub group

The expectation is that the sub group will be closed when it has addressed the specific points set out above. This should be a short review, initiated in January 2018, and will be set up initially for four months, at which point it will be reviewed.

Annex 1: OA Sub group membership

Prof Tim Jickells	University of East Anglia.
Dr Phillip Williamson	NERC and University of East Anglia.
Dr Silvana Birchenough	Centre for Environment, Fisheries and Aquaculture Sciences.
Prof Rachael James	University of Southampton.
Prof Murray Roberts	University of Edinburgh.
Prof Steve Widdicombe	Plymouth Marine Laboratory.
Prof Nick Bates	Joint position at University of Southampton and the Bermuda Institute for Ocean Sciences.
Prof Colin Moffat	Marine Scotland and co-chair of the UK Marine Science Coordination Committee.
Dr Kathryn Dawson	Defra

Appendix 3: Marine carbonate chemistry and the process of ocean acidification

Acidity relates to hydrogen ion (H^+) concentration; it is measured on the inverse logarithmic pH scale, with a change of 1 pH unit equivalent to a ten-fold change in H^+ concentration. Atmospheric CO_2 dissolves into the surface ocean to form carbonic acid, releasing H^+ and causing other chemical reactions; collectively these processes are known as ocean acidification. Most oceanic water is naturally slightly alkaline (above neutral pH of 7.0) as a result of buffering by the ocean's inorganic carbon system. Acidification in the sea is the process of decreasing pH (increasing H^+), in the same way that 'warming' is the process of increasing temperature, whatever the starting point. The extent of OA is modified by chemical reactions (involving carbonate and bicarbonate) in the water column and in sediments, and by interactions with marine plants, animals and microbes, as summarised in **Figure 9**. These interactions include the uptake of CO_2 during photosynthesis (and dissolution of marine carbonates) and its release during the respiration of organic matter (and the biological formation of calcium carbonate via calcification) (Orr et al., 2005, Doney et al., 2009).

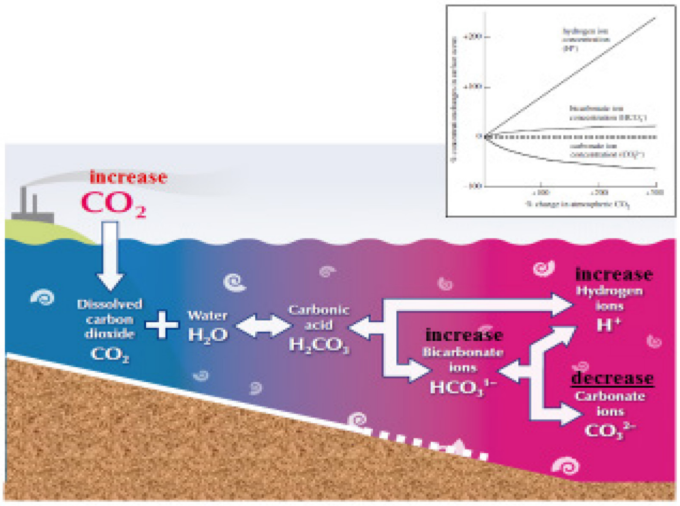

Figure 9: ***Schematic diagram of the chemical reactions initiated after the absorption of atmospheric CO_2 by surface seawater, increasing the concentrations of bicarbonate and hydrogen ions whilst reducing*** *carbonate ions.* **Image courtesy of *Secretariat of the Convention on Marine Biodiversity 2104 An updated synthesis of the impacts of ocean acidification on marine biodiversity. Eds S. Herrige, J.M. Roberts and P. Williamson, Montreal Technical series No 75***

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