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Final Report to OSPAR of the Joint OSPAR/ICES Ocean Acidification Study Group (SGOA)

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ICES CIEM

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Contents

Executive summary

The Joint OSPAR/ICES Study Group on Ocean Acidification (SGOA) was formed to address the eight specific Terms of Reference provided by OSPAR and adopted as a resolution by the ICES 2012 Annual Science Conference and Statutory Meeting. SGOA met three times at ICES Headquarters between 2012 and 2014 and was chaired by Evin McGovern (Ireland) and Mark Benfield (USA). In total 33 scientists representing 12 countries participated in at least one meeting and a number of other experts contributed intersessionally on specific topics. This consolidated report addresses these Terms of Reference, A–H.

ToR A. Collate chemical data and information on ocean acidification in the OSPAR Maritime Area

Many nations are investing resources in ocean acidification (OA) monitoring and research in the North Atlantic, and the current activities of most OSPAR Contracting Parties and the USA are summarized in the report. OA data collection often takes advantage of other marine monitoring activities by adding carbonate system parameters. These activities provide a platform for a coordinated OSPAR monitoring programme, and there is scope for promoting coherence, enhanced quality assurance and data availability to maximise the value and cost-effectiveness of such efforts. Funding commitments are generally short term and project-based despite the clear need to establish long-term time-series. In many areas there are gaps for coastal and inshore information, including estuaries, and for specific offshore benthic habitats such as cold-water coral reefs. There is little OA-specific biological impact monitoring undertaken at present reflecting the immature state of development of OA-impact indicators. However, outcomes from national research projects (such as the UK Ocean Acidification programme and the German BIOACID initiative) may help address that.

ToR B. Seek information from relevant international initiatives on ocean acidification; as listed in OSPAR MIME 11/3/3 (e.g. EU, Arctic Council)

SGOA considered and reported on a range of regional and global initiatives that have provided syntheses of our knowledge of ocean acidification, or have increased/are increasing our understanding of the processes involved. These activities include:

1) Assessments by the Intergovernmental Panel on Climate Change (IPCC; coverage of OA in 5th Assessment Report); Convention on Biological Diversity (CBD; Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity); and by the Arctic Monitoring and Assessment Programme (AMAP).

2) Major EU research projects related to OA and its impacts (EPOCA, MedSeA), and the ocean carbon system (CarboChange).

3) Coordination activities, such as those of the Ocean Acidification International Coordination Centre (OA-ICC) and the Global Ocean Acidification Observing Network (GOA-ON).

ToR C. Finalize guidelines for measuring carbonate system

Guidelines for measuring the carbonate system were adopted by OSPAR in 2014 as part of the suite of Joint Assessment and Monitoring Programme technical guidelines and are available http://www.ospar.org/documents/dbase/decrecs/agreements/14-03e_jamp_oa_guidelines.doc

ToR D. Collect and exchange information on biological effects on plankton, and macrozoobenthos

There has been an exponential increase in the number of publications on biological effects of OA and several recent reviews have covered this topic. The importance of the combined, and frequently interactive, impacts of multiple stressors (such as temperature, low oxygen and pollutants) is now recognised, also the potential for multi-generational adaptation. Experimental research confirms that survival, calcification, growth, development and abundance can all be negatively affected by acidification, but the scale of response can vary greatly for different life stages, between taxonomic groups and according to other environmental conditions, including food availability. Volcanic CO_2 vents can provide useful proxies of future OA conditions allowing studies of species responses and ecosystem interactions across CO_2 gradients. Studies at suitable vents in the Mediterranean and elsewhere show that benthic marine systems respond in consistent ways to locally increased CO_2. At the shelf edge, the ongoing shoaling of carbonate-corrosive waters (with high CO_2 and low pH) threatens cold-water corals, in particular *Lophelia pertusa,* in the Northeast Atlantic. These reefs are rich in biodiversity but we have a poor understanding of their functional ecology, and their responses to the combined effects of future ocean acidification, warming and other stressors.

The greatest effects of projected ocean acidification on zooplankton are likely to be on shelled pteropods ('sea butterflies') in the Arctic and Subarctic. Responses by phytoplankton may be positive, negative or neutral; some calcified species show evidence of multi-generational adaption under experimental conditions. Community-wide planktonic responses to future ocean acidification are likely to be strongly influenced by competitive interactions, that might involve nutrient/food availability and predation, as well as by other environmental changes in a high CO_2 world.

ToR E. Consider the strategy that would be required for an assessment framework appropriate to long-term assessment of the intensity/severity of the effects of ocean acidification, including any assessment criteria required

A draft OA monitoring and assessment strategy is proposed by SGOA for adoption by OSPAR. The proposed strategy would align OSPAR OA monitoring in the Northeast Atlantic with other regional monitoring (e.g. US, Arctic) as well as the vision of the new Global OA Observing Network. In the context of emerging research and the need for long-term (multidecadal) data, the proposed OSPAR framework is flexible and responsive to rapidly expanding scientific knowledge and technological developments. Integrated monitoring approaches that consider OA as one of many ecosystem stressors should be developed, with scope for enhanced cost-effectiveness by adding OA parameters to more well-established monitoring activities, such as those relating to fisheries, eutrophication and Good Environmental Status criteria under the Marine Strategy Framework Directive (MSFD). An initial cycle is proposed to develop coordinated chemical monitoring with a view to establishing a current OA reference dataset (identifying the scale of natural seasonal and spatial variability) with impact indicators added in subsequent cycles as they are agreed. The monitoring strategy emphasises monitoring of vulnerable areas such as the Arctic.

SGOA identified Quality Assurance tools required to support coordinated OA monitoring. These include the need for an expanded range of suitable Reference Materials, provision of routine proficiency testing, additional guidelines, for example on sample preservation and estimating uncertainty of measurement and training. A SGOA/ ICES Marine Chemistry Working Group initiated workshop under the QUASIMEME banner scheduled for 2015 will be a significant step towards addressing these issues.

OSPAR currently use *assessment criteria* in assessments of hazardous substance contamination and eutrophication within their Coordinated Environmental Monitoring Programme. These provide an effective tool of delineating and communicating the environmental "status" (e.g. background/acceptable/unacceptable) of a monitoring station, area or region. SGOA discussed the possible application of assessment criteria for OA monitoring (e.g. deviation in pH or saturation state) but consider that recommendations would be premature. In the context of communicating the threat of OA in the context of the requirement for mitigation or other management action, SGOA expressed concern that, given the inexorable, pervasive and essentially irreversible nature of OA, and our incomplete knowledge of its ecosystem-scale impacts, the concept of assessment criteria as used elsewhere by OSPAR may not be readily transferable to carbonate system parameters. Further consideration is warranted.

ToR F. Inform the development of biological effects indicators for ocean acidification, including the identification of suitable species and key areas

The identification of a limited range of species for monitoring the biological effects of OA (with associated description of appropriate morphological, biochemical or other metrics that can be used to document OA impacts) is currently considered premature. As a first step, SGOA prepared a table of potential indicator taxa and possible quantitative metrics for OA responses. Shell erosion in pteropods (planktonic molluscs) is a potential indicator for the occurrence of low saturation state and its biological consequences, but given the morphological diversity of pteropod shells, identification of suitable species for the OSPAR area and associated metrics are required. One species *Limacina helicina*, is particularly promising as a potential indicator for the Arctic region because it has a broad distribution and a number of studies report its sensitivity to OA. In the absence of specific-species guidelines at present, SGOA recommends that collections are made of a broad suite of species from taxonomic groups likely to be sensitive to OA, and that such samples are archived (without compromising carbonate structures). This archive will serve as a repository of specimens that can be retrospectively examined for evidence of OA responses once appropriate indicator metrics are developed.

SGOA 2013 suggested criteria for selection of suitable species for such monitoring and a 2014 report prepared by Dutch colleagues evaluated pteropods, foraminifera, coccolithophores and mussels as potential organisms. While pteropods and, less clearly, foraminifera contain taxa that were considered potentially suitable, the responses of coccolithophores to OA, particularly *Emiliania huxleyi*, appear to be strain-specific, rendering them unsuitable as indicators at this time. Cold-water corals such as *Lophelia pertusa* are species of high conservation concern and identification of areas where they are currently abundant is important. To this end, new habitat suitability index models developed by NOAA for cold-water corals in the Northwest Atlantic and Gulf of Mexico may prove useful when adapted to the OSPAR area.

ToR G. Elaborate reporting requirements to ICES (taking account of the information in Table at OSPAR MIME 2011 SR Annex 6)

Contracting Parties are required to report OSPAR monitoring data to the ICES DataCentre. OSPAR OA data should also be available to the wider research community via global carbon centres, such as the Carbon Dioxide Information Analysis Centre (CDIAC) in the US, and thus should also meet the reporting requirements of these data centres. The parameters, metadata and checks required for reporting OSPAR OA data to the ICES Environmental Database (ERF 3.2 format) have been defined and tested by SGOA, the Marine Chemistry Working Group and the ICES DataCentre. Contracting Parties are now requested to submit suitable OSPAR OA monitoring data to ICES. This database is best suited to discrete sample data. Although the ICES oceanographic database can take high volume semi-continuous data, for example from sensors, this is not a preferred reporting route as it is limited in its ability to accept associated metadata and QC information. Where OA-monitoring is linked to other monitoring/research activities, for example by adding OA chemistry parameters to monitoring primarily carried out for other purposes, this may define the preferred reporting route for such data. Protocols are needed to facilitate ICES OA data exchange with other international data centres. Data synthesis activities and products that address the ocean carbon system and CO_2 fluxes, such as the Global Ocean Data Analysis Project Version 2 (GLODAPV2) and SOCAT (Surface Ocean CO_2 Atlas), also available via CDIAC, have an additional level of quality checks and should be of benefit to OSPAR.

ToR H. Report a first assessment of all available data in the OSPAR maritime area

In agreement with OSPAR, the above ToR was addressed by focusing on two specific aspects: OA as a threat to cold-water coral reefs; and information on long-term trends in the Northeast Atlantic.

A model-based assessment of current OA status and projected end of century aragonite saturation states indicates that much of the cold-water coral reef habitat in the OSPAR area will be exposed to corrosive waters by the end of the century unless CO_2 emissions are greatly curbed. This is likely to lead to irreversible damage, including habitat loss, to the detriment of important ecological function and services provided by these ecosystems. Research, monitoring and enhanced modelling capabilities are needed to better understand the current conditions to which cold-water corals are exposed; to provide quantitative estimates of the impact of projected future OA conditions on living corals and on habitat structure; and to improve our understanding of the impacts of multiple stressors on coral-based ecosystems and the services they provide.

SGOA collated published information on long-term temporal trends in OA-related chemical parameters in the OSPAR area. While it is not straightforward to compare reported acidification rates, due to different methodologies and approaches (e.g. parameters used, pH scales, timing and frequency of sampling), the studies are consistent in showing acidification of near-surface waters of around -0.02 pH units per decade. Slower rates are generally observed in deeper waters of the Northeast Atlantic, due to the lag time for anthropogenic carbon penetration. Nevertheless, higher rates of acidification and reduction in aragonite saturation may occur in subsurface water masses relative to surface waters.

Together these assessments confirm the progressive and widespread acidification of the North Atlantic and highlight the potential detrimental consequences for ecosystems in the OSPAR region.

Recommendations

To progress the development of coordinated OSPAR monitoring for OA and its impacts SGOA recommends that:

MONITORING STRATEGY	
The draft OSPAR Agreement on a Common Strategy to Enhance Coordinated Monitoring of Ocean Acidification in the Northeast Atlantic (Annex 5) should be considered by OSPAR for adoption to foster implementation of a flexible long-term monitoring and assessment programme in the OSPAR area.	OSPAR
The OSPAR monitoring programme for OA should be initiated as early as possible to ensure high quality long-term datasets can be generated. The lack of specific biological indicators or assessment criteria at this stage should not impede development of monitoring chemical aspects of OA.	OSPAR
The OSPAR monitoring programme for OA should evolve to maximise coherence with other regional (e.g. US and Arctic) and global OA monitoring developments, to ensure data can be harmonized at a North Atlantic scale and contribute to the Global Ocean Acidification Observing Network.	OSPAR
Where feasible, relevant OA parameters should be routinely added to other existing and planned monitoring activities in the OSPAR area with a view to developing long-term and integrated datasets. This includes adding relevant parameters to monitoring of major river discharges, recognising the importance of Quality Assurance for such waters.	OSPAR CPs
The Arctic should be given special prominence in OSPAR OA-monitoring due to its inherent vulnerability to OA.	OSPAR
BIOLOGICAL INDICATORS	
Further work is required to develop a suite of suitable robust, sensitive, and OA-specific biological impact indicators that have wide biogeographical relevance in the OSPAR area.	OSPAR/ICES
A broad suite of organisms (particularly thecosomate pteropods) likely to be sensitive to OA, should be collected and archived. This archive will serve as a repository of specimens that can be retrospectively examined for evidence of OA responses once appropriate indicator metrics are developed. Appropriate techniques for collection and preservation need to be developed.	ICES WGZE/ OSPAR CPs
QUALITY ASSURANCE TOOLS	
There is an urgent need to develop suitable Certified Reference Materials covering a range of salinities and other water quality conditions.	OSPAR/ICES/monitoring community
Routine proficiency-testing for Total Alkalinity and Dissolved Inorganic Carbon should be initiated to support OSPAR monitoring.	QUASIMEME
Following the OA Quality Assurance workshop scheduled for 2015, other QA issues may require the development of guidelines to support harmonised OA monitoring, for example techniques for preservation of samples and estimation and reporting of uncertainty of measurement.	ICES /OSPAR

DATA HANDLING	
OSPAR OA monitoring data and associated QC and metadata should be reported to the ICES *Environmental database* using formats as stipulated by SGOA and MCWG (ERF 3.2 format for discrete sample data). However, this database is not well suited to collect continuous sensor data e.g. pCO_2. The alternative ICES *Oceanographic database* is at present unsuited to the collection of OSPAR OA monitoring data due to limitations in storing relevant QC/method metadata.	OSPAR CPs
OSPAR Contracting Parties should report relevant riverine input data to the OSPAR RID database.	OSPAR CPs, OSPAR INPUT WG
It is further recommended that OSPAR ocean carbon and metadata are reported to the CDIAC international database, according to the internationally standardised formats. OSPAR data in CDIAC should be flagged as such.	OSPAR CPs
ICES should explore the potential for automated data exchange with CDIAC when suitable data are available. The ICES DataCentre should collaborate with other data centres such as NOAA National Oceanographic Data Centre and CDIAC to develop common data exchange and traceability protocols for OA monitoring data.	ICES-DC, CDIAC, NOAA-NODC and other relevant datacentres

SGOA recommends continuation of an ICES OA expert group as a working group	ICES

1 Introduction

1.1 Agenda

The Joint OSPAR/ICES Study Group on Ocean Acidification (SGOA) was formed in 2012 to address the eight specific Terms of Reference provided by OSPAR and adopted as a resolution by the ICES 2012 Annual Science Conference and Statutory Meeting. This follows on from previous ICES advice to OSPAR on ocean acidification (OA) monitoring in 2010 (ICES 2010). These Terms of Reference broadly related to developing harmonised monitoring and assessment capabilities for OA in the Northeast Atlantic taking account of current national, regional and global developments in the field and the current state of knowledge.

The SGOA Terms of Reference as provided by OSPAR were:

a) Collate chemical data and information on ocean acidification in the OSPAR Maritime Area;

b) Seek information from relevant international initiatives on ocean acidification; as listed in OSPAR MIME 11/3/3 (e.g. EU, Arctic Council);

c) Finalize guidelines for measuring carbonate system[1];

d) Collect and exchange information on biological effects on plankton, and macrozoobenthos;

e) Consider the strategy that would be required for an assessment framework appropriate to long-term assessment of the intensity/severity of the effects of ocean acidification, including any assessment criteria required;

f) Inform the development of biological effects indicators for ocean acidification, including the identification of suitable species and key areas[2];

g) Elaborate reporting requirements to ICES (taking account of the information in Table at OSPAR MIME 2011 SR Annex 6);

h) Report a first assessment of all available data in the OSPAR maritime area.

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[1] OSPAR Footnote to ToR c) Building on the draft guidelines coming forwards from ICES Marine Chemistry Working Group (MCWG).

[2] OSPAR Footnote to ToR f) OSPAR BDC, in understanding the interactions between ocean acidification and biodiversity agreed that although it is not possible to identify parameters at this time, there is a need for the monitoring of biodiversity aspects for MSFD to look at the issues of climatic variation and ocean acidification. It was agreed that there are research gaps and hence to put forward a request for advice from ICES to inform the development of OSPAR monitoring tools to detect and quantify the effects of ocean acidification and climate change on species, habitats and ecosystem function, including the identification of suitable species and key areas (OSPAR BDC 2012 SR, Annex 16, §A3).

SGOA met three times 11th–14th December 2012, 7th–10th October 2013 and 6th–9th October 2014 at ICES Headquarters, Copenhagen, Denmark. The meetings were chaired by Evin McGovern (Ireland; OSPAR-nominated chair) and Mark Benfield (USA: ICES-nominated chair). Over the course of the three meetings 33 members and chair-invited experts, representing 12 countries, the Arctic Monitoring and assessment Programme (AMAP) and the ICES DataCentre, participated in at least part of one meeting. In many instances participation was through WebEx. Membership covered a broad spectrum of expertise in chemical and biological aspects of OA, drawn from research and monitoring communities. A number of other experts contributed intersessionally to SGOA activities and products. Of the coastal OSPAR Contracting Parties, France and Portugal were not represented at any of the meetings, although information was received from Portugal. This report to OSPAR, addressing the Terms of Reference, consolidates the outputs of the three SGOA meetings.

More details are available in the annual meeting reports from SGOA.

(ICES 2012, ICES 2013, ICES 2014)

1.2 References

ICES. 2010. “Monitoring methodologies for ocean acidification” Section 1.5.5.2 Special request advice June 2010, ICES Advice 2010, Book 1. International Council for the Exploration of the Sea, Copenhagen http://www.ices.dk/sites/pub/Publication%20Reports/Advice/2010/Special%20Requests/OSPAR%20Monitoring%20methodologies%20for%20ocean%20acidification.pdf.

ICES. 2012. Report of the Joint OSPAR/ICES Ocean Acidification Study Group (SGOA), 11–14 December 2012, Copenhagen, Denmark. ICES CM 2012/ACOM:83. 75pp. http://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/acom/2012/SGOA/sgoa_2012.pdf

ICES. 2013. Report of the Joint OSPAR/ICES Ocean Acidification Study Group (SGOA), 7–10 October 2013, Copenhagen, Denmark. ICES CM 2013/ACOM:31. 82 pp. http://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/acom/2013/SGOA/sgoa_2013.pdf

ICES. 2014. Report of the Joint OSPAR/ICES Ocean Acidification Study Group (SGOA), 6–9 October 2014, Copenhagen, Denmark. ICES CM 2014/ACOM:33. 32 pp. http://www.ices.dk/sites/pub/Publication%20Reports/Expert%20Group%20Report/acom/2014/SGOA/sgoa_2014.pdf

2 ToR A: Collate chemical data and information on ocean acidification in the OSPAR Maritime Area

A number of nations are carrying out OA monitoring, with related research, in the OSPAR region and the wider North Atlantic. These activities were summarised by national members of SGOA. While this information may not be complete[3], it provides a good overview of diverse data-gathering activities. There are relevant monitoring/research activities (covering CO_2 fluxes and a range of carbonate chemistry parameters, in addition to pH *per se*) in most, if not all, the OSPAR contracting parties. Annex 4 tabulates known OA observational activities in the Northeast Atlantic; the focus is on chemical parameters, and is a continuation of work initiated for the ICES Cooperative Research Report "Chemical Aspects of Ocean Acidification Monitoring in the ICES Marine Area" (Hydes *et al*., 2013).

2.1 Overview and general observations of OA monitoring in the North Atlantic

Figure 1 provides an indicative map of current and planned OA-directed monitoring activities in the OSPAR region, as carried out by OSPAR contracting parties with focus on chemical measurements. The following general observations were made by SGOA in relation to these ongoing activities:

- Many countries are currently investing resources in monitoring the ocean carbon system and in establishing an ocean acidification 'baseline' (while recognising that this is dynamic and can be highly variable on many time-scales). There are variations in the approaches taken by different countries, and in some cases the sampling activities co-occur in geographically complementary regions. This provides an important opportunity for intercalibration and collection of statistically robust data. Promotion of coherence in monitoring and data exchange would facilitate more efficient use of these resources.
- OA monitoring activities often take advantage of other ongoing monitoring or platforms (e.g. hydrographic, fisheries surveys) by adding additional carbonate system measurements. This ensures cost-effective and valuable data collection, although such an approach may not necessarily be optimized for OA monitoring.
- SGOA sees the maintenance of established time-series and the establishment of new long-term time-series in appropriate locations as essential. However, the funding for much of the current monitoring activities is often short term (finite-life projects) and few resources are currently committed to securing consistent long-term observations.
- There are particular gaps for coastal and inshore information, and for specific offshore benthic habitats expected to be sensitive to OA impacts; there is also a

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[3] Of the OSPAR countries, no information was available to SGOA on French OA monitoring activities as France was not represented at SGOA. Some information on French activities is provided in Annex 4.

need to synthesize data at both national and international levels. However, temporal and spatial variability in OA parameters can be high, and many areas that are of interest for monitoring the changes in, and impacts of OA, lack adequate biological or chemical time-series that could be used to assess the ecological significance of observed future changes.

- There are few stations where biological (e.g. effects) monitoring is taking place alongside chemical monitoring. Where it does occur, quite high level or general indicators tend to be used and not OA-specific effects monitoring. This reflects the immature stage of development of biological effects indicators of OA. In some cases carbonate parameters have been added to existing biological time-series monitoring such as that undertaken in the Barents Sea as part of the ecosystem surveys performed in a Norwegian-Russian collaboration.

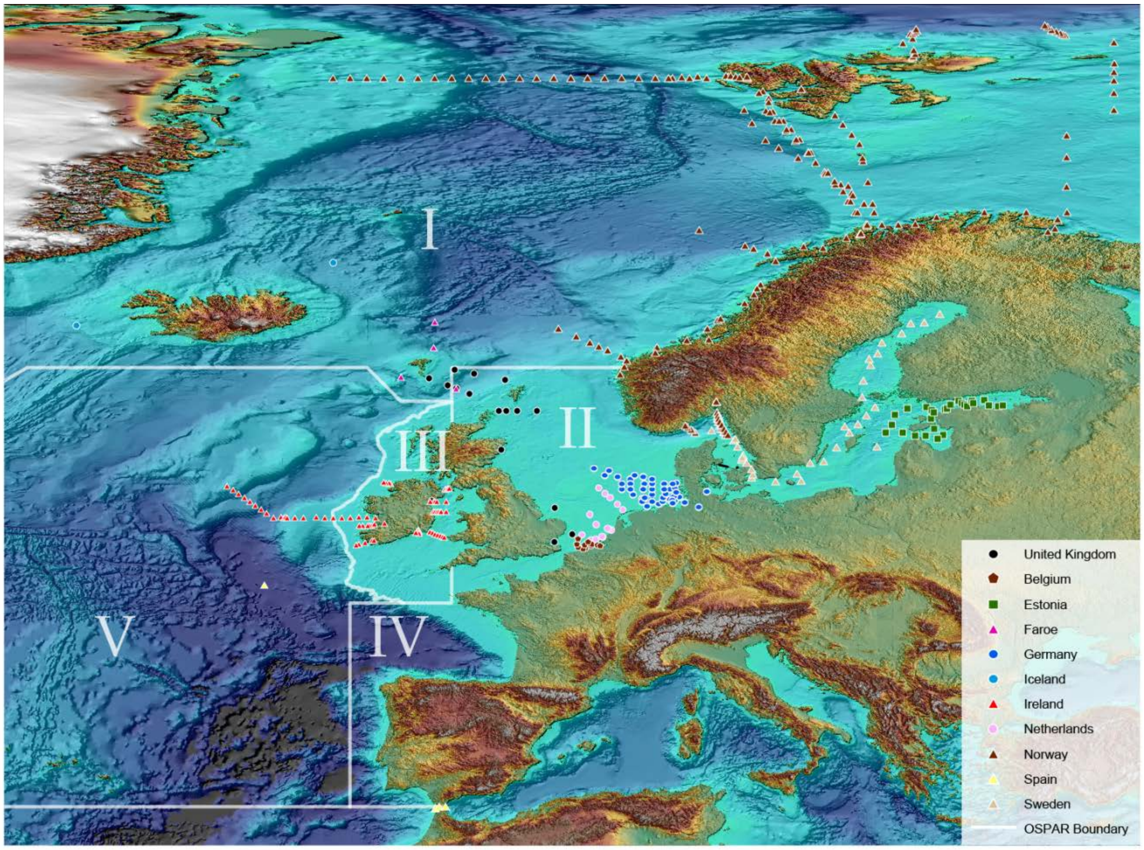


Figure 1. Map of repeat measurement sites for OA monitoring purposes in the Northeast Atlantic and Baltic Sea based on information provided to SGOA. Note this map should not be considered definitive.

2.2 Monitoring in Belgian waters

National marine monitoring

The national monitoring programme in Belgium runs under the responsibility of the Operational Directorate Natural Environment (former MUMM), part of the Royal Belgian Institute of Natural Sciences (RBINS), to comply with the commitments made pursuant to international conventions. Physico-chemical observations include oxygen (since the 1980s), pH (since 1985), nutrients (since end 1980s), DOC/POC (since 2000), PN (since 2000), total alkalinity (since 2014), heavy metals (since early 1980s), organic pollutants (since approximately 1985), chlorophyll, salinity, temperature, and conductivity. Dissolved Inorganic Carbon (DIC) measurements will start soon. Ten stations in Belgian waters are repeatedly monitored at a frequency of 4 to 12 times per year or measured during transects using a FerryBox or CTD. The data are collected, managed and stored in the Belgian Marine Data Centre (http://www.mumm.ac.be/datacentre/) and circulated to scientists, ICES and decision-makers.

Related research

Research-oriented OA observations have also been carried out on the carbonate chemistry of the Belgian part of the North Sea (BPNS) (Borges and Frankignoulle 1999; 2002; 2003; Schiettecatte *et al.*, 2006; Borges *et al.*, 2008; Gypens *et al.*, 2004; 2009; 2011; Borges and Gypens, 2010). The carbonate chemistry of the BPNS is strongly influenced by the Scheldt estuary leading to a river plume with salinities ranging from ~29 to ~35‰. This leads to very strong spatial gradients in carbonate chemistry between the Scheldt mouth and the most offshore part of the BPNS. Due to strong tidal currents and the shallowness of the BPNS (<30 m depth), the water column is permanently well-mixed, hence, there are no vertical gradients of the carbonate chemistry variables. The major drivers of the carbonate chemistry on the BPNS are the inputs of low pH and high CO_2–loaded waters from the Scheldt estuary that lead to low pH and high pCO_2 values in winter and the spring phytoplankton bloom (dominated in biomass and production of *Phaeocystis*) that leads to low pCO_2 and high pH, followed by the degradation of organic matter during summer and fall leading to maximal pCO_2 and minimal pH values in fall. In addition to CO_2, the DIC levels in the BPNS are also controlled by the inputs from the Scheldt of highly alkaline waters (Frankignoulle *et al.*, 1996; Borges *et al.*, 2008).

Further research focused on biogeochemical models that allowed historical reconstructions of the decadal changes of carbon cycling and carbonate chemistry in the BPNS over the period 1951 to 1998 in response to the increase of atmospheric CO_2 and nutrient delivery by rivers (Gypens *et al.*, 2009; Borges and Gypens, 2010).

Information provided by Kris Cooreman, Alberto Borges at SGOA 2014.

2.3 Monitoring in Danish waters

There is no coordinated collection of ocean acidification in the Danish marine monitoring programme NOVANA, but pH is measured in connection with primary production, mainly by pH-electrodes. Some data on total alkalinity is also available, and Duarte *et al.* (2013), have collected and quality assured (i.e. filtered obvious bad values) a dataset from literature and monitoring data from the beginning of 1900 to 2011 (large gaps in data before 1978). They find that the main difference in pH in top and bottom waters are due to the ratio of production and respiration, and that around 0.03 pH units (10–15%) of the increase in pH can be attributed to CO_2 in the atmosphere, based on aggregated data for top and bottom waters for both Danish fjords and open water stations respectively. There is both a seasonal variation and variation in the water above and below the pycnocline. A graph of Danish Straits' pH data (1953–2010) is given in Duarte *et al*. (2013).

Information provided by Martin Larsen at SGOA 2012.

2.4 Monitoring in German waters

The BSH (Federal Maritime and Hydrographic Agency, Hamburg, Germany) is continuing monitoring in the German Bight (EEZ - exclusive economic zone) to meet monitoring requirements within OSPAR and the MSFD. Water samples from the surface and near the bottom and sediment samples are taken at about 40 stations for analysis of trace metals, organic pollutants, nutrients, pH, chlorophyll, oxygen (August/September) and salinity four times a year. CTD data are taken at each station. During the monitoring cruises continuous pH measurements and continuous phosphate and silicate measurements are carried out.

In 2013 the BSH laboratory started flow-through pCO_2 measuring in the "measurement bunker" of the Alfred Wegener Institute/Biological Institute Helgoland (AWI/BAH). These continuous pCO_2 analyses are ongoing. High-resolution temperature, salinity and pH measurements are taken in parallel.

During the summer monitoring cruise 2014 the BSH monitoring programme was supplemented by measuring total alkalinity (GRAN method). The spatial distribution of pH and TA are shown in Figure 2. The temporal pH trend in the German Bight (Figure 3) shows a decline of 0.03 units over the period 1990–2014.

German research on OA impacts is carried out at a range of institutions, primarily through the BIOACID programme (Biological Impacts of Ocean Acidification); see Section 2.15.2 below.

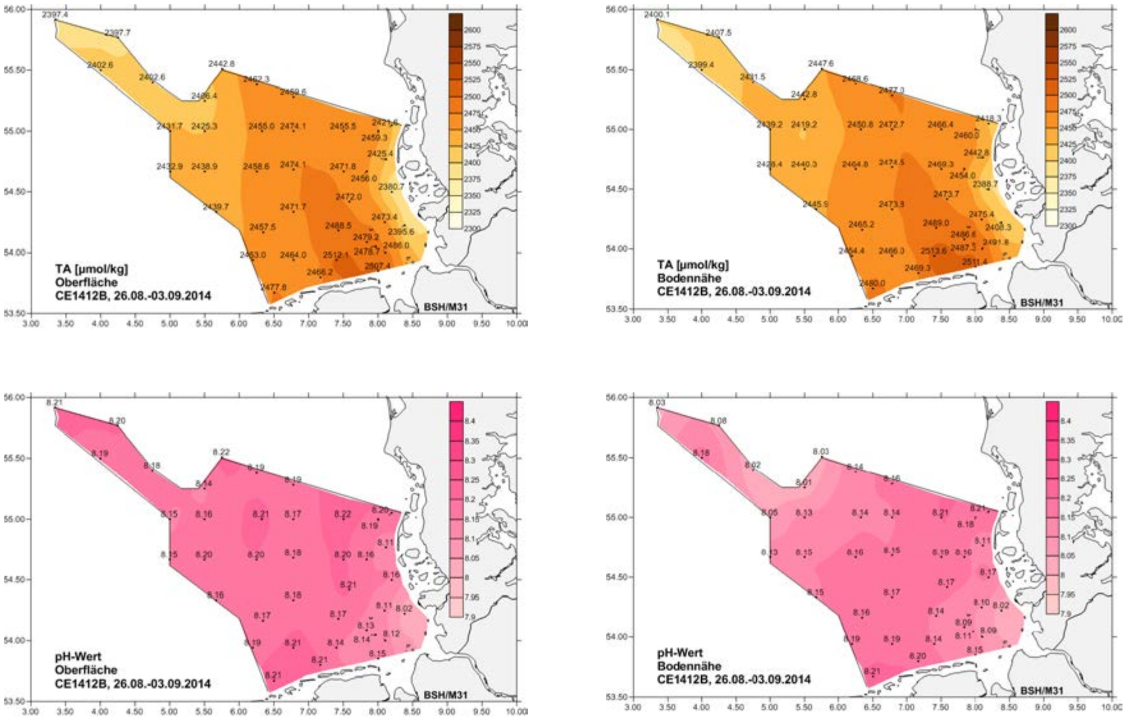


Figure 2. Spatial distribution of TA [µmol/L] (top) and pH (bottom) in surface seawater (left) and near bottom water (right) during the summer monitoring cruise (26 August to 7 September 2014).

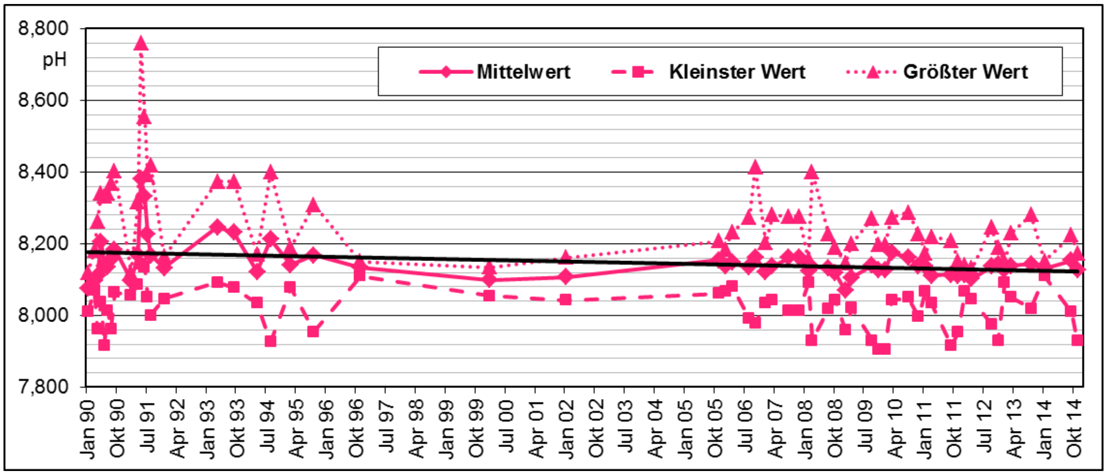


Figure 3. Temporal pH trend in the German Bight (January 1990 to November 2014). Mittelwert, mean value; Kleinster Wert, minimum value; Gröβter Wert, maximum value.

Information provided by Sieglinde Weigelt-Krenz (BSH, Germany), updated SGOA 2014.

2.5 Monitoring in Dutch waters

National marine monitoring

There is no coordinated collection of CO_2 parameters in the Dutch monitoring programme (MWTL), but pH is measured as part of eutrophication monitoring.

pH has been measured from 1975 onwards at 249 stations, mainly with electrodes on NBS scale. Data were analysed for long-term trends by Provoost *et al.* (2010). In the Dutch section of the North Sea, pH at non-coastal stations increased between 1975–1985, then subsequently declined (at the rate of 0.02 to 0.03 units per year, Figure 4) between 1998–2006. At coastal stations (in the Wadden Sea, Eastern and Western Scheldt and Ems-Dollard estuary) different patterns of pH change occurred. This variability can probably be attributed to changes in the production/respiration balance driven by changes in eutrophication.

Currently, pH is measured within the monitoring programme at 19 stations with a frequency of 4–19 times a year, and is also measured at high frequency on a transect (Terschelling) using ferry box and CTD.

Related research

The Royal Netherlands Institute for Sea Research (NIOZ) carried out fine-scale measurements of DIC, total alkalinity (TA), pCO_2 and pH, together with other relevant parameters, on research cruises with RV Pelagia in 2001, 2002, 2005, 2008 and 2011, covering 95 stations in basin wide North Sea (OSPAR II) (Figure 5). These data revealed a general decrease in pH from 2001–2011. NIOZ also measured DIC and TA at a fixed station (NIOZ jetty) on a weekly to monthly basis from 2008–2010. NIOZ has plans to continue ship-based monitoring and to expand two existing fixed time-series stations with continuous pCO_2, pH and O_2 measurements. There has been no structured monitoring programme for biological indicators or sensitive species.

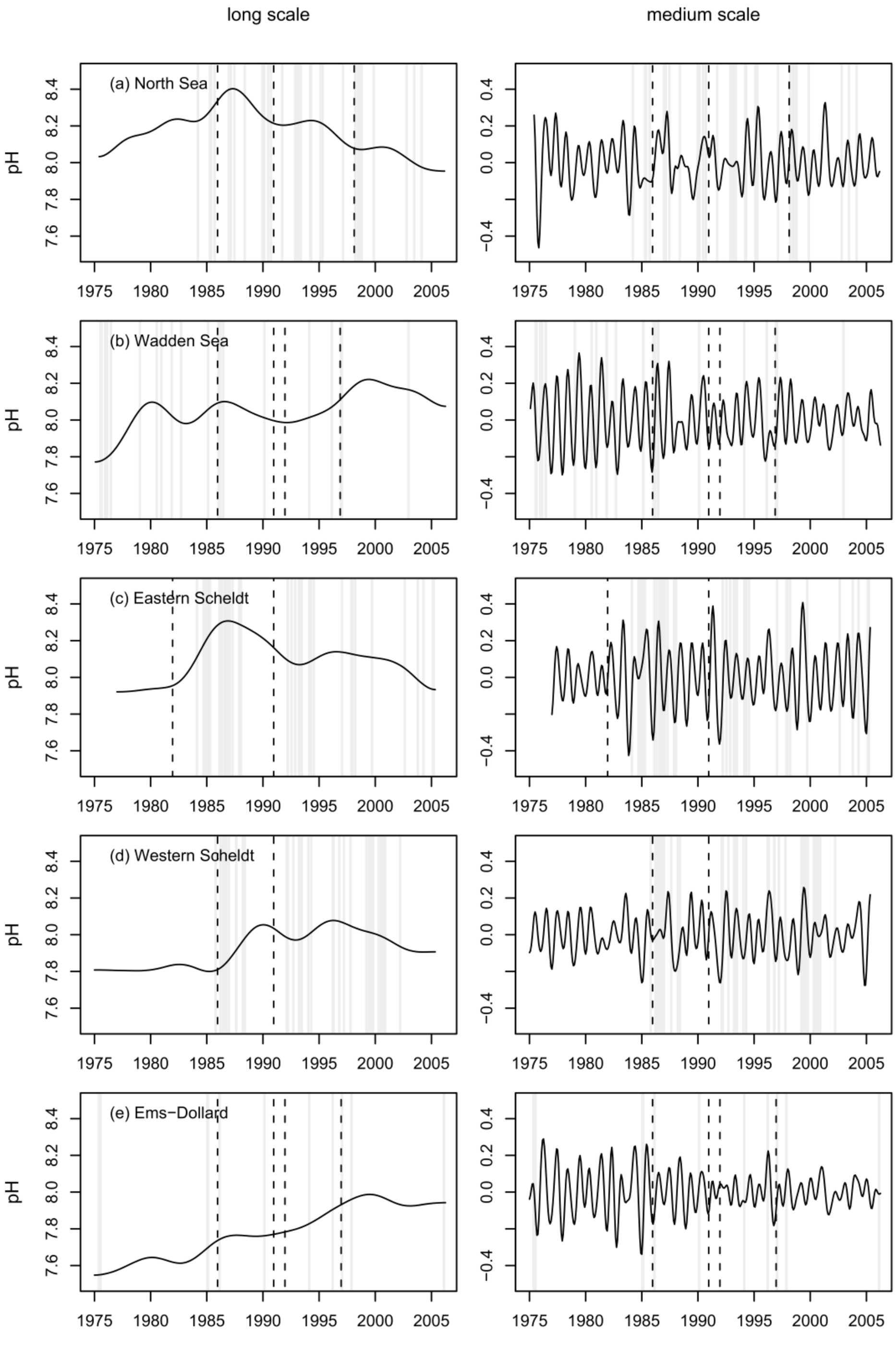


Figure 4. Long-term trends and medium variability of pH in the Dutch North Sea, Wadden Sea and Dutch estuaries (from Provoost *et al.*, 2010).

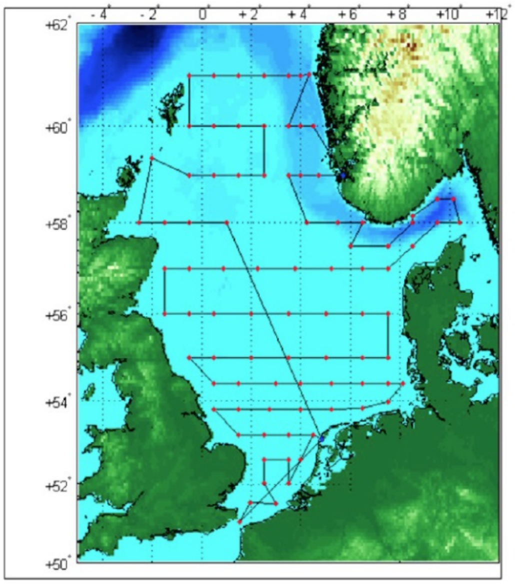


Figure 5. Cruise track from RV Pelagia in 2011, with nearly identical locations in preceding years.

Information provided by Anna de Kluijver; updated SGOA 2014

2.6 Monitoring in Faroese waters 2014

The Faroe Marine Research Institute, Havstovan, conducts four standard hydrography cruises each year, in February, May, June and August/September.

The project "Establishing monitoring of ocean acidification and CO_2 in the Arctic" (Etablering af monitoring af havforsuring og CO_2 i Arktis) is funded by DANCEA. The project takes advantage of the existing hydrographic programme and has chosen five stations and six standard depths where samples are taken. At all six depths alkalinity and total inorganic carbon will be analysed with a VINDTA 3c instrument and a Dickson standard will be run every day of analysis. In addition, nutrients, salinity, temperature and other physical parameters are collected (Figure 6).

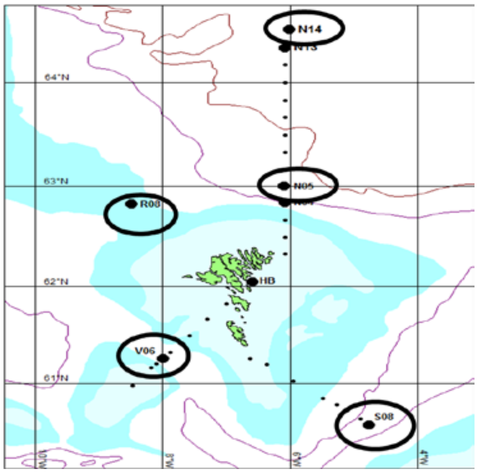


Figure 6. Stations selected for OA monitoring in Faroese waters.

Information provided by Maria Chun Nielsdóttir SGOA 2014.

2.7 Monitoring in Icelandic waters

The Marine Research Institute in Iceland measures inorganic carbon at two time-series stations, one in the Irminger Sea to the west of Iceland, the other one in the Iceland Sea north of Iceland. The programme is run parallel with the hydrographic monitoring programme. Quarterly measurements started for surface waters in 1983 and a full profile has been taken from 1991. Parameters measured from discrete samples are DIC, pCO_2, O_2, salinity and nutrients. In addition underway pCO2 measurements are made on these cruises.

Since 1993, MRI has also conducted research on carbon cycle parameters on other locations in Icelandic waters as a part of different, short-term research programmes. From 1993–1996 effort was made to measure the seasonal changes in the surface (0–200 m) waters with up to 13 cruises annually, first in the Irminger Sea in 1993 and then in the Iceland Sea from 1994–1996. In 2010 measurements for OA studies were carried out in areas south of Iceland where cold-water corals are found and the seasonal cycle of carbon cycle parameters was established in Breiðafjordur Fjord in West Iceland where coralline algae beds are found. From 2006–2008 in connection with the Iceland Sea programme operated by MRI, measurements were done on two sections in the Iceland Sea. Fisheries surveys have also been exploited as a platform for OA sampling and, in a 2013 survey going into the East Greenland current north of the Denmark Strait, underway pCO_2 and discrete OA parameters sampling was done. In 2013 a surface OA mooring was deployed in the Iceland Sea. The mooring was developed and deployed by the NOAA - Pacific Marine Environmental Laboratory.

Information provided by Sólveig Ólafsdóttïr; updated SGOA 2014.

2.8 Monitoring in Irish waters

As part of a nationally funded project (2008–2011), the Irish Marine Institute and NUI Galway undertook a baseline study on the carbonate system in Irish coastal, shelf and off-shelf waters. Some initial pCO_2 measurements and CO_2 flux studies were undertaken at NUI Galway's Mace Head station (a Global Atmospheric Watch station) and on board the RV Celtic Explorer. An initial assessment compared data obtained for the southern Rockall Trough with WOCE survey data from the same area in the 1990s. An increase in anthropogenic carbon (ΔC_{ant}) of ~1 µmol kg^{-1} yr^{-1} was estimated for subsurface winter-mixed layer waters of the Rockall Trough between 1991 and 2010. This equates to a calculated pH reduction of 0.02 pH units per decade (McGrath *et al.*, 2012), in line with observations reported in other time-series for the North Atlantic. Decreases in pH were also calculated for deeper water masses over the 19 year period including Labrador seawater (LSW) at 1500–2000 m deep a decrease in pH of ~0.015 units per decade was calculated. Sampling of TA, DIC and nutrients on a hydrographic standard section on the shelf to the west of Ireland (53°N) and in the southern Rockall Trough has been continued (McGrath *et al.*, 2013) and TA, DIC sampling has also been included with ship based winter environmental sampling in Irish coastal and inshore shelf waters. A current project is investigating the carbonate chemistry of coastal and estuarine waters including seasonal aspects and riverine inputs (McGrath *et al.*, in press).

Information provided by Evin McGovern; updated SGOA 2014.

2.9 Monitoring in Norwegian and Arctic waters

A detailed overview of OA monitoring by Norwegian authorities was included in the SGOA 2012. Two major programmes were outlined as below:

- Climate and Pollution Agency (KLIF) "Monitoring OA in Norwegian waters" KLIF changed name in 2013 to Norwegian Environment Agency (Miljødirektoratet).
- Ocean Acidification Flagship at the FRAM-High North Research Centre for Climate and the Environment, funded by Ministry of Climate and Environment (KLD) and Ministry of Trade, Industry and Fisheries (NFD).

Detailed information and maps on the Norwegian OA monitoring is found in the annual reports from this program (Chierici *et al.*, 2013; 2014). Data from the monitoring programme was recently used to report on trends and changes in the carbonate system in the Greenland and Norwegian Sea showing increased CO_2 due to anthropogenic uptake resulting in decreasing pH between 0.07 to 0.13 in the period from 1981 to 2013 (Skjelvan *et al.*, 2013; Skjelvan *et al.*, 2014).

Further information was provided to SGOA 2013 on additional activity in the project in the OA Flagship, FRAM, in the programme "Monitoring Svalbard and Jan Mayen" (MOSJ) led by the Norwegian Polar Institute. MOSJ is mainly a biological monitoring programme where the Institute of Marine Research (IMR) initiated OA studies in July 2012. This ongoing activity aims to monitor carbonate system (OA state) in Svalbard fjords and also water column sampling for TA and DIC at about eight to ten stations in Kongsfjorden and Rijpfjorden.

Information provided by Melissa Chierici.

2.10 Monitoring in Portuguese waters

There is currently no national monitoring programme in Portugal. The Portuguese Institute for the Sea and Atmosphere (IPMA) has conducted hydrographic surveys and collected samples for DIC and TA measurements over several years in specific areas along the coast, covering mainly the areas influenced by the major Portuguese rivers (Tagus and Douro). In early 2013, IPMA undertook a winter survey over the continental platform covering the entire coast, the first of this kind, and collected samples for DIC and TA.

In 2015 two surveys are planned for seamount areas (from continental Portugal to Madeira) and measurements will be undertaken at some fixed stations along the Portuguese coast, with a monthly sampling frequency. Since 2013, the Azores University is also making measurements in an area of shallow-water hydrothermal vent in Azores.

Information provided by Marta Nogueira; updated SGOA 2014.

2.11 Monitoring in Spanish Atlantic waters

Spanish research relevant to the monitoring and assessment of ocean acidification is carried out by a number of institutions and includes both time-series stations and repeat sections. The ocean observation activities in the OSPAR region that include carbonate system measurements are:

Time-Series Stations:

- ESTOC (Canary Island, led by Melchor González Dávila and Magdalena Santana, University of Las Palmas de Gran Canaria);
- Deployment of pH sensor at PAP station in the North Atlantic in collaboration with NOC Southampton (UK) from July 2014;
- GIFT (Gibraltar, led by Emma Huertas, CSIC-ICMAN of Cadiz).

Repeated sections:

- OVIDE (Portugal-Greenland), French-Spanish collaboration (LPO and CSIC-IIM, led by Herlé Mercier and Fiz F. Pérez);
- FICARAM (Falkland-Cartagena), Spanish initiative (CSIC-IIM led by Fiz F. Pérez);
- VOS lines: QUIMA (UK-South Africa), (now moving to a new ship company) led by Melchor González Dávila and Magdalena Santana Casiano.

At present there are two different observation systems taking carbon measurements at the Strait of Gibraltar: the GIFT time-series itself (composed of three stations), run by the Consejo Superior de Investigaciones Científicos (CSIC-ICMAN and IIM) and started in 2005; and a mooring line, set up in 2011, placed in one of the stations that form the GIFT. The mooring line contains SAMI sensors and current meters and is managed by the CSIC and the Spanish Institute of Oceanography (IEO).

Information provided by Patrizia Ziveri; updated SGOA 2014.

2.12 Monitoring in Swedish waters

The Swedish Hydrology and Metrology Institute (SMHI) undertakes monthly monitoring cruises around the coast of Sweden (Skagerrak, Kattegat and the Baltic Proper) visiting a network of 23 stations. At these stations water samples are taken for analysis of nutrients, oxygen, chlorophyll *a*, salinity and temperature. At six of these stations the OA parameters pH (NBS scale) and alkalinity are measured. Once a year SMHI extend the monitoring cruise to Bothnian Bay, where samples for measurements of pH and alkalinity are taken at three stations.

pH measurements during the time interval 1997–2007 show a significant decrease in pH for all the waters around Sweden, with the largest changes in the Baltic Proper (Figure 7).

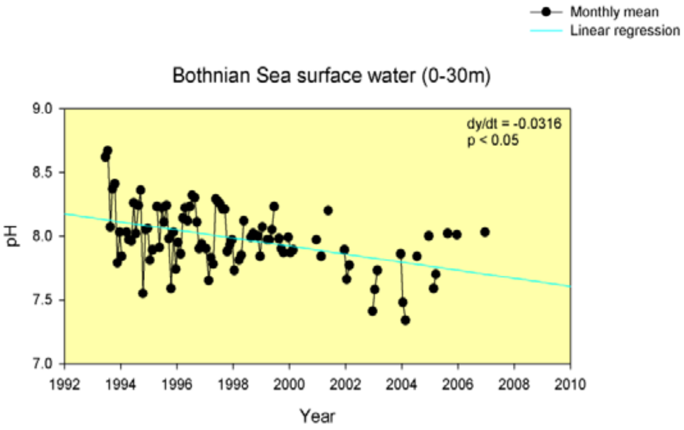


Figure 7. Long-term trends of pH in the Bothnian Sea. (Andersson *et al.*, 2008).

The Gulf of Bothnia is monitored by the University of Umeå, and the University of Stockholm also makes observations at two stations in the monitoring network.

SMHI has two buoys in the open sea, one at the West Coast and one in the Baltic Proper. During 2014 six smaller buoys have been placed in Swedish coastal waters. These buoys measure salinity, temperature, oxygen, chlorophyll *a* and turbidity.

In 2011 SMHI installed an underway system for $p\mathrm{CO}_2$ measurements in a FerryBox system. This system is currently not functioning but will soon be operational. A new underway fluorometric pH system is currently under development.

Information provided by Anna Willstrand Wranne, (SMHI) at SGOA 2014.

2.13 Monitoring in UK waters

2.13.1 Activities by Cefas

The Centre for Environment, Fisheries and Aquaculture Science (Cefas) established time-series stations in late 2010 at three SmartBuoy sites in the Southern North Sea (Warp, West Gabbard and Dowsing). Discrete samples for TA and DIC analyses are collected 4–8 times a year at these sites. Additional spatial coverage in the North Sea, Channel, Celtic

Sea, Irish Sea and Liverpool Bay was also started in late 2010, with discrete samples for TA and DIC analyses being collected on annual fisheries and other environmental monitoring cruises. The absolute values and spatial patterns of DIC data from the North Sea in July/August 2011 (preliminary data in Williamson *et al*., 2013) showed good agreement with previous surveys at the same time of year (e.g. Bozec *et al*., 2006). In addition, surface measurements taken during a UKOA cruise in 2011 showed good agreement with Cefas data collected in the North Sea a few weeks later.

An underway pCO_2 system was fitted to RV Cefas Endeavour in January 2012 and has been successfully used since then on fishery assessment (and other) cruises. Together with underway data from MRV Scotia (see below), this system will provide spatial coverage for a high proportion of UK waters and European shelf seas. Although any specific site/area may only be sampled 1–2 times per annum, coverage will be repeated at closely similar times of year. Comparisons between measured pCO_2 and values calculated from TA/DIC samples collected during two cruises in September and October 2012 show good agreement, with a root mean squared error (RMSE) of between 10 and 15 µatm. Current support for these monitoring activities is provided through the PLACID project (see Section 2.15.5).

To provide baseline data (currently lacking) for pH in natural sediments, Cefas obtained cores in summer 2011 and early 2012 at 30 stations from contrasting sea regions (temperature, depth, sediment type) in the North Sea and Channel. Profiles of pH and dissolved oxygen were obtained using microelectrodes; these showed pH reductions of 0.5–1.0 in the top centimetre of muddy sands. These data were supplemented with sediment profile imagery (SPI) visuals, particle size analysis and organic carbon analyses. The results offer insights into factors affecting natural pH variability within a variety of sediments under current conditions.

2.13.2 Activities by Marine Scotland Science

Water samples for TA and DIC analysis have been collected weekly by Marine Scotland Science since 2008 at the Stonehaven long-term coastal monitoring site (~20 km south of Aberdeen), both at the surface (1 m) and just above the seabed (45 m). An initial assessment of this dataset (Walsham *et al*., 2014), showed strong seasonal variability linked to phytoplankton growth and nutrient uptake. Studies of coccolithophores at the Stonehaven site indicated that two morphotypes of *Emiliania huxleyi*, types A and B, occur there.

Surface to seabed seawater samples were also collected in 2012 for TA/DIC analysis along transect lines in the Faroe/Shetland channel (Nolso to Flugga, and Fair Isle to Munken) and the Atlantic inflow line (Orkney to Shetland); details are given in Walsham *et al.* (2014). Underway pCO_2 samples, with wide spatial coverage, have been collected on MRV Scotia surveys since 2013.

2.13.3 Additional activities

Additional UK monitoring relevant to OA and its potential impacts includes the Continuous Plankton Recorder survey (CPR, www.sahfos.ac.uk) and sites providing long-term data on the abundance of a diverse range of pelagic and benthic organisms (e.g. the century-long time-series off Plymouth; www.westernchannelobservatory.org.uk). CPR and

ICES datasets have been recently analysed to see if ocean acidification effects could be detected in the changing abundances of potentially sensitive, calcifying species. However, evidence of the occurrence of any such signals is currently inconclusive (Beaugrand *et al.*, 2013; Beare *et al.*, 2013).

Details of other UK research initiatives on OA and its impacts are given below (Sections 2.15.3–2.15.5), with support through the UK Ocean Acidification research programme, the Shelf Sea Biogeochemistry programme, and by Cefas/Defra projects. A wider national monitoring framework is provided by the inter-agency UK Integrated Marine Observing Network (UK-IMON, www.uk-imon.info).

Information provided by David Pearce, Pam Walsham, Caroline Kivimae and Phil Williamson; updated SGOA 2014.

2.14 Monitoring in US Atlantic waters

The ocean acidification observing system along the US East and Gulf of Mexico coasts has been conducted under the direction of the Atlantic Oceanographic and Meteorological Laboratory of the US National Oceanic and Atmospheric Administration (NOAA). The project focuses on obtaining inorganic carbon data to map and forecast aragonite saturation states, Ω_{Ar} along the East and Gulf coasts employing a strategy of measurements from research ships and ships of opportunity (SOOP) while taking advantage of other monitoring activities, such as the Coastal OA Mooring Program sponsored by US Ocean Acidification Program (OAP). The data along with remotely sensed data are used to create maps of increasing fidelity and resolution along the East and Gulf coasts with a robust validation approach and uncertainty analysis. The underway data are providing the key *in situ* observations to create the Ω_{Ar} maps in the form of T, S, and pCO_2 measurements (Figure 8). The main measurements are the temperature, salinity, and underway pCO_2 measurements. Several ships have oxygen, nitrate and pH sensors in order to improve the OA products.

The cruises in the areas of interest are given in Figure 8, with the left panel showing representative cruise tracks of *Gunter* and *Bigelow,* the middle panel showing the representative cruise tracks of ships and data under our groups, and the right panel all underway pCO_2 data from SOOP up to 2012 in the surface ocean carbon atlas (SOCAT) database.

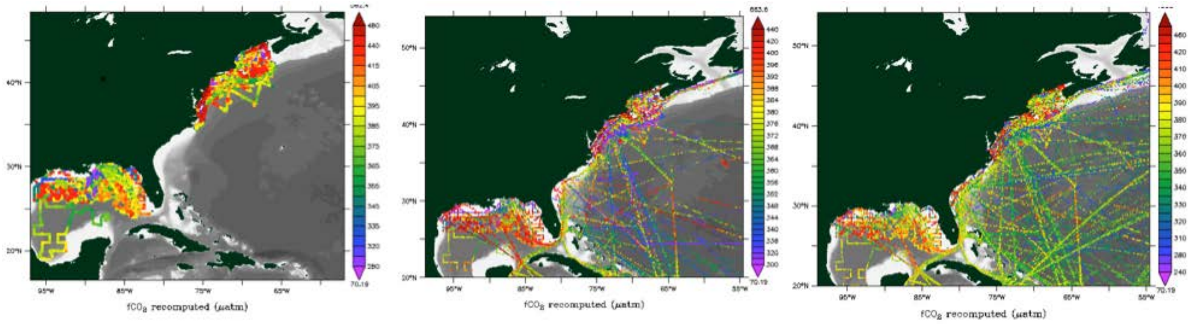


Figure 8. Cruise tracks of *Gunter* (GOM) and *Bigelow* (NE) involved in stock assessments and mammal surveys (left). Cruise tracks of ships operated by the AOML carbon group (middle), and all tracks in the region (right). Data are from the SOCAT database (www.socat.info) using the LAS server with surface concentration in colour code (legend right).

The data are used for production of surface water ocean acidification products. The approach is based on creating relationships between pCO_2 and temperature, and utilizing established relationships between TA, temperature and salinity to obtain two inorganic carbon parameters that in turn are used to fully constrain the OA product suite. An example for the Northeast coast based on the cruises of the *Bigelow* is shown in Figure 9.

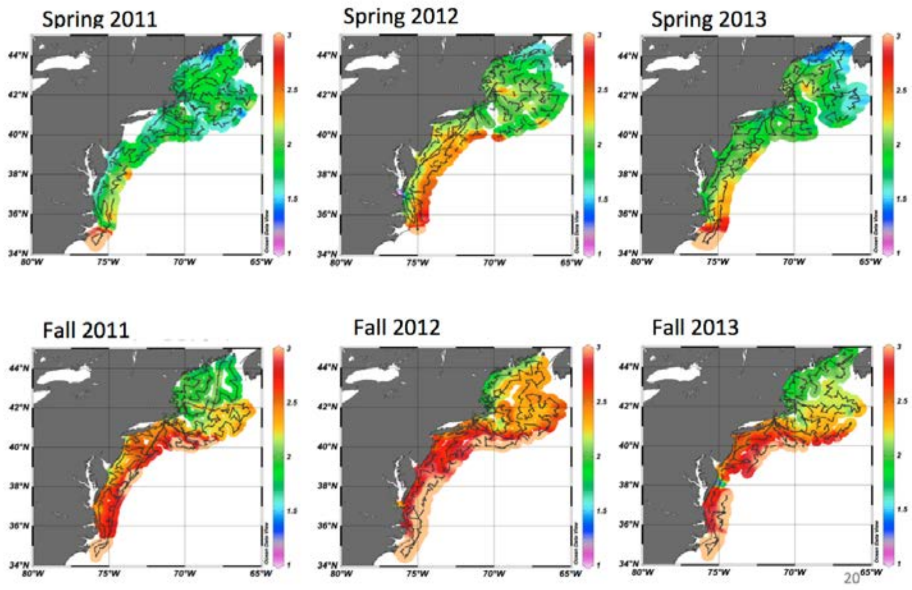

Spring 2011
Spring 2012
Spring 2013
Fall 2011
Fall 2012
Fall 2013

Figure 9. Aragonite saturation state (Ω_{Ar}) calculated from salinity–alkalinity relationships and pCO_2 for three years of SOOP-OA measurements in the Northeast US utilizing the salinities and pCO_2 measurements from the Bigelow.

The approach is described in Gledhill *et al.* (2008, 2009) where OA products were created using the underway data and remote sensing for the Caribbean. The algorithms underlying the approach are updated when new understanding, sensors, and data are available.

Differences in Ω_{Ar} in between cruises in 2005 and 2012 are shown in Figure 10. The expected decrease in Ω_{Ar} due to invasion of anthropogenic CO_2 over the five years is ≈0.1.

The much larger changes, both positive and negative, show the determining influences of coastal biogeochemical processes, riverine outflow and coastal currents on Ω_{Ar}.

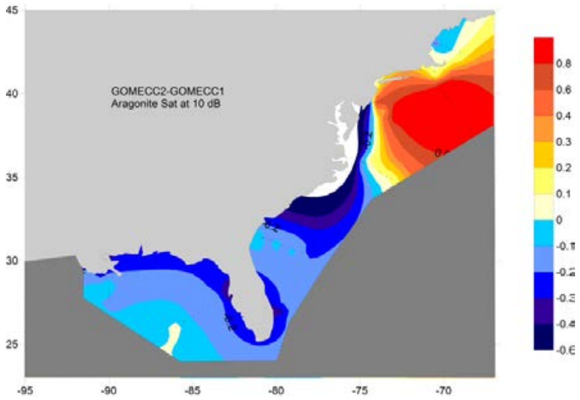


Figure 10. Differences in aragonite saturation state (Ω_{Ar}) estimated from cruises in 2005 and 2012 along the 10 dbar isosurface. Data from the cross-shelf transects are extrapolated and binned in 0.5-degree grids and then subtracted.

Further information on US OA monitoring in US Atlantic waters is available in the SGOA 2012 report. Information provided by Richard Feely, Beth Phelan, and Sharon Meseck (SGOA 2012 and SGOA 2014).

2.15 Other major national research activities providing information on OA and its impacts

2.15.1 4DEMON project (Belgium)

Over the last four decades, numerous scientific expeditions at sea have resulted in a vast quantity of scientific data and important publications in the scientific literature about the marine environment of the Belgian continental shelf. Many valuable, historic data however still remain inaccessible to the larger scientific community, being available only on paper in various institutions. These sources may be very helpful for understanding long-term changes in the quality of the marine environment. A new project, the 4DEMON project (http://www.4demon.be/) commenced in March 2014 and aims to centralise, integrate and evaluate all Belgian data on contamination, eutrophication and ocean acidification compiled during expeditions in the BPNS over the last four decades, forming an important Belgian scientific heritage.

2.15.2 Biological Impacts of Ocean Acidification: BIOACID (Germany)

A major research initiative in recent years is the German project 'Biological effects of Ocean acidification' (BIOACID), currently in phase II and involving 15 research institutes; details at **http://www.bioacid.de**. The BIOACID project is investigating organism responses in various ecosystems; their consequences for ecosystem functioning, studied in mesocosms and laboratory experiments; and socio-economic implications. Some of these ecosystems differ with respect to their physico-chemical background characteristics; furthermore, organism taxa and life stages display different responses and response sizes. For example:

- Arctic pteropods respond to elevated CO_2 levels by reduced calcification, shell dissolution, and elevated mortality of larvae and juveniles.
- The Arctic coralline red algae *Lithothamnion glaciale* shows a strong negative response.
- Growth and production of inorganic material decreased in the calcifying macroalgae *Corallina officinalis* L.
- The cold-water coral *Lophelia pertusa* displays acclimation to ocean acidification during long-term exposure.
- In sea urchin larvae digestion and calcification are negatively impacted.
- Juvenile sea stars decrease feeding and growth with no acclimation potential.
- Elevated CO_2 decreased growth of the Oyster *Crassostrea gigas.*
- Atlantic herring and cod larvae develop severe tissue damage when exposed to elevated CO_2 levels.
- Juvenile mussels *Mytilus edulis* revealed how food availability can increase resilience to ocean acidification.

In the Baltic the highly variable conditions in Kiel Fjord include high background levels of ambient CO_2 and seem to be a "training factor" for organism resilience. Accordingly, communities from Kiel Fjord are much better able to deal with future CO_2 conditions than their counterparts from less "stressful" habitats like the Wadden Sea.

Further findings suggest significant changes in the microbial diversity under anthropogenic pressures such as global warming and ocean acidification; bacterial growth can be stimulated under CO_2. Increasing CO_2 supports the production and exudation of carbon-rich components, enhancing particle aggregation and settling, but also provides substratum and attachment sites for bacteria. Toxin production in Baltic cyanobacteria was stimulated by high CO_2. Phytoplankton biomass declined with warming but there was no clear trend under elevated CO_2. Ciliate biomass declined during a phytoplankton bloom. However, elevated CO_2 stimulated the productivity of picophytoplankton, diazotrophic cyanobacteria and dinoflagellates, whereas the productivity of diatoms was reduced. As seen before, shifts from larger to smaller species occurred at elevated temperatures. Furthermore, more labile organic carbon and higher bacterial abundance can increase rates of oxygen consumption and may intensify the risk of oxygen depletion in coastal seas. All of these findings indicate that ecosystems may shift to new steady states, characterized by new and unforeseen patterns of species predominance and interactions.

Hans Otto Pörtner, SGOA 2014.

2.15.3 UK Ocean Acidification research programme (UKOA)

In addition to the monitoring work of Cefas and Marine Scotland Science (Section 2.13 above), many other research centres, university groups and other organisations are involved in relevant research and assessment with carbonate chemistry components, and associated research, developed through the UK Ocean Acidification research programme

(UKOA, 2010-2015; www.oceanacidification.org.uk), jointly funded by the Natural Environment Research Council (NERC), the Department of Environment, Food and Rural Affairs (Defra) and the Department of Energy and Climate Change (DECC).

UKOA has provided support for, *inter alia*:

- Initial establishment of carbonate chemistry monitoring in UK water;
- national involvement in the Surface Ocean CO_2 Atlas (SOCAT, http://www.socat.info/ e.g. Bakker *et al*., 2014);
- high-resolution modelling studies for European shelf seas (e.g. Artioli *et al*., 2012; 2014);
- experimental studies of biological responses to OA, with emphasis on long-term, multi-stressor impacts (e.g. Godbold and Solan, 2013);
- palaeo-studies, to investigate the impacts of previous, naturally driven perturbations to the ocean carbonate system.

UKOA has also supported four multidisciplinary research cruises over the period 2011–2013, directed at the biotic and biogeochemical consequences of carbonate chemistry changes, off northwest Scotland (with focus on cold-water corals); around the UK; in the NE Atlantic and Arctic; and in the Atlantic sector of the Southern Ocean. DIC, TA, pH and pCO_2 data were collected on all these UKOA cruises, with additional water column information, including $\delta^{13}C$ and standard physical oceanographic measurements.

'Over-determination' of carbonate parameters on UKOA cruises showed good agreement between independently determined variables (Ribas-Ribas *et al*., 2014). Biological analyses have included coccolithophore abundance, species composition, and species-specific measures of coccolith size and calcification (Poulton *et al*., 2014). Although considerable variability of these parameters was found, there were no first order relationships relating them to the pH ranges or other aspects of carbonate chemistry, e.g. calcite saturation state (Young *et al*., 2014).

Phillip Williamson, SGOA 2014.

2.15.4 UK Shelf Sea Biogeochemistry programme (SSB)

The UK Shelf Sea Biogeochemistry programme (SSB, 2013–2018; www.uk-ssb.org), co-funded by NERC and Defra, is directed at carbon and nutrient cycling, with a fieldwork focus on production processes and shelf edge exchange for the Celtic Sea. Although ocean acidification *per se* is not an SSB priority, many SSB studies on carbon dynamics are highly relevant. In particular, a spatially extensive (see map) survey of carbonate chemistry parameters is being carried out in 2014–2015, with involvement of international partners.

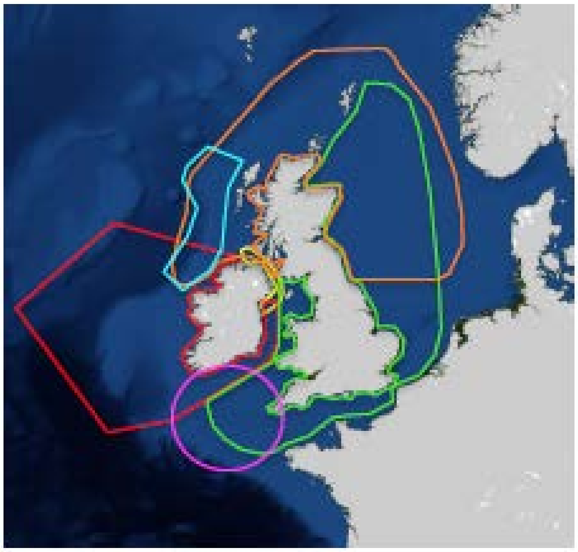


Figure 11. Spatially extensive sampling for carbonate chemistry parameters coordinated by SSB programme, 2014–2015, involving CTD and underway sampling. Components and partners: SSB cruises (Celtic Sea, pink); AFBI (north Irish Sea, yellow); Cefas (North Sea, Channel, Celtic Sea, Irish Sea; green); Marine Scotland Science (Scottish waters, orange); Irish Marine Institute (Irish waters, red); NOC/ NERC (Outer Hebrides cruise, blue). Also ship of opportunity lines (not shown).

The outcome of the SSB survey will be seasonal and monthly surface maps of air-sea CO_2 flux, surface dissolved inorganic nutrient, DIC, TA, DOM, salinity and temperature; also cross-shelf sections of carbonate and nutrient chemistry, and measurement of annual net air-sea CO_2 flux, with uncertainties.

Phillip Williamson and Caroline Kivimae, SGOA 2014

2.15.5 Defra/Cefas OA research (UK)

The UK Department for Environment, Food and Rural Affairs (Defra) supports three Ocean Acidification/Climate Change research projects at the Centre for Environment, Fisheries and Aquaculture Science (Cefas), as summarised below.

2.15.5.1 Placing Ocean Acidification in a wider Fisheries Context (PLACID)

The PLACID project provides support for the collection of Cefas OA monitoring data (TA, DIC, pCO_2) for UK territorial waters, beyond the end of the UKOA programme, as detailed in 2.13. It is currently exploring the possibility of working with the Environment Agency to collect more inshore samples to characterise the fauna distribution. PLACID has three other objectives, relating to OA impacts on commercially important shellfish and fish:

i) Carry out multi-factorial experiments (considering different life stages) to investigate the effects of OA and other stressors (temperature, pH, oxygen) on commercial species. These studies are carried out in Cefas' OA experimental facility at Weymouth. Juvenile lobster and cockle larvae studies have been completed, and experiments on whelks are planned.

ii) Use Dynamic Energy Budget (DEB) models to 'scale up' from a detailed knowledge of physiology to population-scale effects, with the aim of assessing the economic consequences resulting from OA on fisheries. This is based on how an organism uses energy during different types of stress periods and has looked at copepod larvae.

iii) Quantify the economic impact of OA on UK shellfish and aquaculture industries based on how OA will affect the different species in future and what would it mean for the UK economy.

2.15.5.2 Maritime Industries-Environmental Risk and Vulnerability Assessment (MINERVA)

The MINERVA project includes studies of multiple stressors and cumulative effects. These aspects are supported by laboratory experiments to determine consequences of interacting pressures on marine organisms and associated industries; e.g. the cumulative impact of warmer seawater, ocean acidification, reduced oxygen, and other human stressors. Experiments have been carried out on the combined impact of pH and metals (from a dredged material site) on an invasive species, the slipper limpet *Crepidula fornicata*.

2.15.5.3 Impacts from climate change and ocean acidification on Fisheries and Marine biodiversity (IFMA)

The IFMA project is conducting experiments to establish critical oxygen levels (the concentration at which a fish can maintain resting metabolic rate) for sea bass under different temperature, pH/CO_2 and oxygen scenarios. Cefas' internal funding (Seedcorn) supports numerical simulations of water temperature and dissolved oxygen concentrations. This work will be able to overlay the results onto projections of North Sea oxygen and pH/CO_2 levels, to assess potential effects on spawning, feeding, migration and other behaviours.

David Pearce, SGOA 2014.

2.15.6 Effects of ocean acidification on organisms in northern waters (ECOAN) within the FRAM OA flagship programme (Norway)

This is a multidisciplinary project initiated in 2012 and further developed to determine the variability of pH and CO_2 chemistry focusing on the Barents Sea and Arctic Ocean, and to predict the resulting physiological and evolutionary effects in animal populations in these waters (Figure 12). The present knowledge of the major drivers of change in pH and CO_2 uptake in northern waters is scarce, and we do not have sufficient knowledge to predict the ecological effects. The project provides unique and new data in a changing region with poor data coverage. Predictions of future changes will be based on studies of natural-regional CO_2 chemistry variability and anthropogenic perturbations combined with output from model simulations. Using laboratory experimentation, physiological effects and evolutionary adaptive responses of three key ecosystem species from this region (copepods, pteropods, and cold-water corals) is being investigated. A multi-stressor approach is applied, investigating the combined effects of decreasing pH, increasing temperature, and surface water freshening. The results will be used to provide a stakeholder friendly synthesis of the time frame of expected biological effects. Using existing modelling tools, subsequent impacts on fish stocks in the area will be estimated, and the entailing socio-economic consequences considered. The knowledge obtained will inform policy-makers involved in fish stock- and ecological management on future effects of OA and Arctic change.

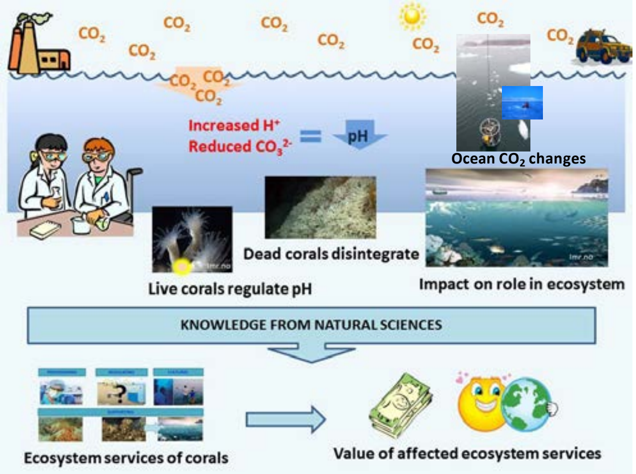


Figure 12. A schematic view of the multidisciplinary work performed in the FRAM flagship programme "Ocean Acidification and effects in northern waters" Compiled by: Jannike Falk-Petersen, Norut.

2.16 References

Andersson, P., Håkansson, B., Håkansson, J., Sahlsten, E., Havenhand, J., Thorndyke, M., Dupont. S. 2008. Marine Acidification, On effects and monitoring of marine acidification in the seas surrounding Sweden. SMHI Oceanografi nr 92, http://www.smhi.se/polopoly_fs/1.1985!oceanografi_92%5B1%5D.pdf.

Artioli Y., Blackford J.C., Butenschön M., Holt J.T., Wakelin S.L., Thomas H., Borges A.V. and Allen J.I. 2012. The carbonate system in the North Sea: Sensitivity and model validation. J. Marine Systems, 102–104, 1–13Y.

Artioli, Y., Blackford, J. C., Nondal, G., Bellerby, R. G. J., Wakelin, S. L., Holt, J. T., Butenschön, M., and Allen, J. I.: Heterogeneity of impacts of high CO2 on the North Western European Shelf. 2014. Biogeosciences, 11: 601–612, doi:10.5194/bg-11-601-2014-2014.

Bakker D.C.E., Pfiel B., Smith K. and 78 others. 2014. An update to the Surface Ocean CO_2 Atlas (SOCAT version 2). Earth Syst. Sci. Data, 6: 69–90; doi: 10.5194/essd-6-69-2014.

Beare, D., McQuatters-Gollop, A., van der Hammen, T., Machiels M., Teoh S.J. and Hall-Spencer J. 2013. Long-term trends in calcifying plankton and pH in the North Sea. *PLoS ONE* 8, e61175; doi: 10.1371/journal.pone.0061175.

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; doi: 10.1038/nclimate1753.

Borges A.V. and Frankignoulle, M. 1999. Daily and seasonal variations of the partial pressure of CO_2 in surface seawater along the Belgian and southern Dutch coastal areas. Journal of Marine Systems 19: 251–266.

Borges A.V. and Frankignoulle, M. 2002. Distribution and air-water exchange of carbon dioxide in the Scheldt plume off the Belgian coast. Biogeochemistry 59(1–2): 41–67.

Borges A.V. and Frankignoulle. M. 2003. Distribution of surface carbon dioxide and air-sea exchange in the English Channel and adjacent areas. Journal of Geophysical Research, 108 (C5), 10.1029, doi:2000JC000571.

Borges A.V., Ruddick, K. Schiettecatte, L.-S. and Delille, B. 2008. Net ecosystem production and carbon dioxide fluxes in the Scheldt estuarine plume, BMC Ecology, 8:15, doi:10.1186/1472-6785-8-15.

Borges A.V. and Gypens, N. 2010. Carbonate chemistry responds more strongly to eutrophication than ocean acidification in the coastal zone, Limnology and Oceanography, 55: 346–353.

Bozec, Y., Thomas H., Schiettecatte L.-S., Borge A.V., Elkalay K. and Baar H.J.W. 2006. Assessment of the processes controlling seasonal variations of dissolved inorganic carbon in the North Sea. Limnol. Oceanogr. 51: 2746–2762.

Chierici, M., I. Skjelvan., R. Bellerby., M. Norli., L. Lunde Fonnes., H. Hodal Lødemel., K.Y. Børsheim., K. S. Lauvset., T. Johannessen., K. Sørensen., E. Yakushev. 2014. Overvåking av havforsuring i norske farvann, Rapport, Miljødirektoratet, TA218-2014.

Chierici, M., Sørensen, K., Johannessen, T., Børsheim, K.Y., Olsen, A., Yakushev, E., Omar, I., Skjelvan, A., Norli, M., Lauvseth, S., Blakseth, T.A. 2013. Tillførselprogrammet 2012, Overvåking av havsførsuring av norske farvann, Rapport, Klif, TA3043 2013.

Duarte, C.M., Hendriks I.E., Moore T.S., Olsen Y.S., Steckbauer A., Ramajo L., Carstensen J., Trotter J.A. and McCulloch M. 2013. Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. Estuaries & Coasts, 36: 221–236.

Frankignoulle M., Bourge, I. and Wollast, R. 1996. Atmospheric CO_2 fluxes in a highly polluted estuary (The Scheldt), Limnology and Oceanography, 41 (2): 365–369.

Gledhill D. K., Wanninkhof, R., Millero, F. J. and Eakin, C. M. 2008. Ocean acidification of the Greater Caribbean Region, Journal of Geophysical Research - Oceans, 113(C10).

Gledhill, D.K., Wanninkhof, R. and Eakin, C.M. 2009. Observing ocean acidification from space. Oceanography, 22(4):48–59.

Godbold, J. and Solan, M. 2013. Long-term effects of warming and ocean acidification are modified by seasonal variation in species responses and environmental conditions. *Phil. Trans. Roy. Soc. B.,* 368, 20130186; doi: 10.1098/rstb.2013.0186.

Gypens N., Lancelot, C. and Borges A.V. 2004. Carbon dynamics and CO_2 air-sea exchanges in the eutrophicated coastal waters of the Southern Bight of the North Sea: a modelling study, Biogeosciences, 1(2): 147–157.

Gypens N., Borges, A.V. and Lancelot, C. 2009. A model study of the evolution during the past 50 years of air-sea CO_2 fluxes in the Belgian coastal zone (Southern Bight of the North Sea), Global Change Biology, 15(4): 1040–1056.

Gypens N., Lancelot, C., Lacroix, G. and Borges, A.V. 2011. Seasonal and inter-annual variability of air-sea CO_2 fluxes and seawater carbonate chemistry in the Southern North Sea, Progress in Oceanography, 88: 59–77.

Hydes, D. J., McGovern, E., and Walsham, P. (Eds.) 2013. Chemical aspects of ocean acidification monitoring in the ICES marine area. ICES Cooperative Research Report No. 319. 78 pp. International Council for the Exploration of the Sea. Copenhagen. http://www.ices.dk/sites/pub/Publication%20Reports/Cooperative%20Research%20Report%20(CRR)/crr319/ICRR%20NO319%20web.pdf

McGrath, T., Kivimäe, C., Tanhua, T., Cave, R. R., and 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.

McGrath, T., Kivimäe, C., McGovern, E., Cave, R. R., and Joyce, E. 2013. Winter measurements of oceanic biogeochemical parameters in the Rockall Trough (2009–2012). Earth System Science Data, 5: 375–383.

McGrath, T., McGovern, E., Cave, R. R., Kivimäe, C. In press. Inorganic Carbon Chemistry in Coastal and Shelf Waters around Ireland. Estuaries and Coasts. DOI: 10.1007/s12237-015-9950-6.

Poulton A.J., Stinchcombe M.C., Achterberg E.P., Bakker D.C.E., Dumousseaud C., Lawsoin H.E., Lee G.A., Richier S.M., Suggett D.J. and Young J.R. 2014. Coccolithophores on the north-west European shelf: calcification rates and environmental controls. Biogeosciences, 11: 3919–3940; doi:10.5194/bg-11-3919-2014.

Provoost, P., van Heuven, S., Soetaert, K., Laane, R.W.P.M. and Middelburg, J. J. 2010. Seasonal and long-term changes in pH in the Dutch coastal zone, Biogeosciences, 7: 3869–3878, doi:10.5194/bg-7-3869-2010.

Ribas-Ribas M., Rérolle V.M.C., Bakker D.C.E., Kitidis V., Lee G.A., Brown I., Achterberg E.P., Hardman-Mountford N.J. and Tyrrell T. 2014. Intercomparison of carbonate chemistry measurements on a cruise in northwestern European shelf seas. Biogeosciences 11: 4339–4355; doi: 10.5194/bg-11-4339-2014.

Schiettecatte L. S., Gazeau, F. Van der Zee, C. Brion, N. and Borges, A.V. 2006. Time series of the partial pressure of carbon dioxide (2001–2004) and preliminary inorganic carbon budget in the Scheldt plume (Belgian coast waters), Geochemistry, Geophysics, Geosystems (G3), 7: Q06009, doi:10.1029/2005GC001161.

Skjelvan, I., E. Jeansson, M. Chierici, A. Omar, A. Olsen, S. Lauvset, T. Johannessen. 2014. Havforsuring og opptak av antropogent karbon i de Nordiske hav, 1981–2013, Rapport, Miljødirektoratet, M244-2014.

Skjelvan, I., Olsen, A., Omar, A. and Chierici, M. 2013. Rapport fra arbeidet med å oppdatera havforsuringsdelen av Forvaltningsplanen for Norskehavet. Direktoratet for Naturforvaltning, Norge.

Walsham P., Webster L., Engelke C., Greenwood N., Stewart B., Kivimae C., Hartman S., Pearce D and Gowen R. 2014. UK Ocean Acidification Coastal Monitoring Network: Expanding the UK Network (Defra Contract C5801/ME5309). Scottish Marine and Freshwater Science, 5(1) (http://www.scotland.gov.uk/Resource/0044/00442616.pdf)

Williamson, P., Turley, C., Brownlee, C., Findlay, H.S., Ridgwell, A., Schmidt, D.N., Schroeder, D.C., Blackford, J., Tyrrell, T. and Pinnegar, J.K. 2013. Impacts of ocean acidification. MCCIP Science Review 2013, 34-48, doi:10.14465/2013.arc05.034-048.

Young J.R., Poulton A.J. and Tyrrell T. 2014. Morphology of *Emiliania huxleyi* coccoliths on the northwestern European shelf – is there an influence of carbonate chemistry? Biogeosciences, 11: 4771–4782; doi:10.5194/bg-11-4771-2014.

3 ToR B: Seek information from relevant international initiatives on ocean acidification; as listed in OSPAR MIME 11/3/3 (e.g. EU, Arctic Council)

3.1 Arctic Monitoring and Assessment Programme (AMAP)

The Arctic Ocean Acidification Assessment (AOA) was produced by AMAP for the AOA Conference in Bergen in May 2013 and for the Arctic Council Ministerial meeting, in May 2013. The assessment is divided into five chapters: 1) sets the stage for the assessment; 2) presents an introduction to the carbon biogeochemical system in the Arctic Ocean; 3) provides a description of the biological responses to ocean acidification; 4) presents analyses of how changes in ocean acidification may affect the economics of marine fisheries, food security and cultural issues for coastal Arctic indigenous communities; and 5) presents an overall summary of the major findings and gaps in knowledge of Arctic Ocean acidification.

The assessment presents ten Key Findings, covering ocean chemistry, biological responses and socio-economic implications of Arctic OA. In the recommendations, it is noted that the biological, social, and economic effects of ocean acidification are potentially significant for the Arctic nations and their peoples, as well as global society. In the recommendations there is a call for the Arctic Council to enhance research and monitoring efforts that expand the understanding of acidification processes and their effects on Arctic marine ecosystems and northern societies that depend on them.

The outreach products of the assessment are 1) a scientific report http://www.amap.no/documents/doc/AMAP-Assessment-2013-Arctic-Ocean-Acidification/881; 2) a layman's summary report; 3) a summary for policy-makers; and 4) a film. The reports are available at http://amap.no/documents/, and the film is available at http://www.amap.no/documents/doc/arctic-ocean-acidification-2013-full-version/803.

A planned updated assessment will have a focus on assessing the societal impacts of ocean acidification in the Arctic. This will be done through a series of case studies that can be either regional, geographical or socio-economic, but should be predominantly driven by ocean acidification. In addition, the assessment will address tele-connections, i.e. transport of carbon to and from the Arctic and the associated processes, including the impact on global oceans. Finally the assessment will contain information on new and updated information that has become available since the 2013 report. The new assessment will be published in 2017.

Jan Rene Larsen, AMAP.

3.2 International Panel Climate Change (IPCC) 5th Assessment Report

OA was considered as a cross-cutting theme in the IPCC 5th Assessment Report (AR5) report http://www.ipcc.ch/index.htm, with coverage by both Working Groups I and II. The findings of WG II with respect to the impacts of climate change and OA are summarised in Section 5.4 of this report.

3.3 Convention on Biological Diversity: Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity

The Convention on Biological Diversity (CBD) was one of the first international bodies to raise concern about the impacts of ocean acidification (Secretariat of the Convention on Biological Diversity, 2009). It has recently produced an updated synthesis of scientific information on this topic (Secretariat of the Convention on Biological Diversity, 2014), with associated decisions at its 12th Conference of Parties that included urging Parties and inviting "other Governments, the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization, relevant scientific groups, and other relevant organizations, to further enhance their international collaboration to improve the monitoring of ocean acidification, closely linked to other global ocean observing systems, noting that a well-integrated global monitoring network for ocean acidification is crucial to improve understanding of current variability and to develop models that provide projections of future conditions" (CBD 2014).

The updated CBD report notes that ocean acidification is currently occurring at a geologically unprecedented rate, subjecting marine organisms to additional environmental stress. Attention is drawn to the extent of natural temporal and spatial variability in seawater pH, also that biological responses can also be highly variable, interacting with other stressors and with some potential for genetic adaptation. Ongoing policy interest in ocean acidification by UN bodies and other international organisations is summarised in the CBD report, also the current status of global observations. For the latter, the role of the Global Ocean Acidification Observing Network (see Section 6.2) is highlighted, recognising the need to greatly increase the coverage and coordination of both chemical and biological monitoring. While the differing sensitivities of a wide range of benthic and pelagic taxa to OA impacts are discussed in the main body of the CBD report, no attempt is made to shortlist species or groups that might be particularly suitable for monitoring purposes.

Phil Williamson, UK.

3.4 EU-funded (FP7) research projects relevant to OA

Information on three EU-funded projects, MedSeA, EPOCA and CarboChange, is given below. The OA-relevant parts of the EU KnowSeas project are discussed in Section 5.2.2, and ICOS is mentioned under Section 3.5.

3.4.1 MedSeA: Mediterranean Sea Acidification in Changing Climate

The European MedSeA project focusing on ocean acidification in the Mediterranean Sea was finalized in 2014 and results were presented to the SGOA by Patrizia Ziveri, the MedSeA project coordinator. Currently, the MedSeA is the only EC FP7 project focusing on OA research. It had a regional approach assessing uncertainties, risks and thresholds related to Mediterranean OA. To make reliable OA projections, it was key to consider the combined effects of OA and warming. This applies particularly in the Mediterranean, a region considered a hot-spot for climate change. The results included the outcomes from laboratory experiments, field studies in naturally acidified waters, and monitoring sites. Mediterranean CO_2 vent studies converge in showing the effects of OA on benthic systems. These effects include a reduction of calcareous species and biodiversity, and alteration of the competitive dynamics between species with "regime shifts" (Milazzo *et al.*, 2014; Baggini *et al.*, 2014; Taylor *et al.*, 2014; Ziveri *et al.*, 2014). In addition, the ocean warming and heat waves may intensify the effects of acidification (Rodolfo-Metalpa *et al.*, 2011).

Long-term OA laboratory experiments on target organisms were used in the project to detect the physiological impacts. For example, a 314-day laboratory experiment has demonstrated the detrimental effects of OA on the precious endemic Mediterranean red coral, *Corallium rubrum* (Bramanti *et al.*, 2013). The economically important species *Mytilus galloprovincialis* is largely used in the Mediterranean aquaculture industry. Results from a one-year long experiment focusing on the combined effects of OA and warming, clearly showed that mortality rates increase dramatically in the high temperature treatments, regardless of the pH conditions. All mussels died at high temperature, towards the end of the experiment, and around 50% of the mussels remained at ambient temperature. The loss of periostracum was evident on mussels exposed to low pH conditions after summer warm conditions (Gazeau *et al.*, 2014). These results corroborated a previous MedSeA field study based on CO_2 vents (Rodolfo-Metalpa *et al.*, 2011).

Interestingly, results obtained from a first questionnaire-based study of Mediterranean bivalve mollusc producers from 12 coastal regions and six countries (including those with the highest production share in the Mediterranean region) are assessing knowledge and perception of threat of climatic and non-climatic environmental stressors among the Mediterranean aquaculture industry. The results suggest that OA is still a relatively unknown phenomenon and generally not well understood. Moreover, it is considered a secondary threat compared to other pressures. Summer heat waves are currently perceived as the highest threat, having been observed in a majority of the studied production sites in past years, with effects on seed (spat), adult mortality, and byssus attachment (Rodrigues *et al.*, in review).

Recent work had demonstrated that OA in the Northwest Mediterranean Sea is already detectable, with a decrease of 0.0016 unit yr-1 between 1998–2000 and 2003–2005 (Meier *et al.*, 2014), close to rates observed in other areas of the ocean (Orr, 2011). Furthermore, datasets from the northwestern Mediterranean Sea indicate that in the 18-year period 1995–2013 alone, acidity has already increased more than 10%. Projections of CO_2 emissions indicate a sustained uptake of anthropogenic carbon in the ocean and a 30% increase in acidification between years 2010 and 2050 if we continue to emit CO_2 at the same rate. This implies, since the industrial revolution and within only a few decades, acidification of the Mediterranean Sea is likely to increase by 60%, and by 150% at the end of the century (MedSeA project publications are in preparation).

Assessment of selected socio-economic impacts of OA for some target Mediterranean region are in the process of being published or finalized (Rodrigues *et al.*, 2013; Ghermandi *et al.*, 2014; Rodrigues *et al.*, in review).

Adaptation and mitigation strategies, and policies at global, regional and local scales need to be implemented as they are the only certain, effective way to reduce CO_2 emissions to the atmosphere and associated ocean acidification. Mediterranean Sea acidification may be more severe in areas where human activities and impacts, such as nutrient run-off from agriculture, further increase acidity. Agricultural run-off from land and other pressures linked with human activities on Mediterranean ecosystems needs to be more strictly regulated. In addition, adaptation policies are required as an increase in atmospheric CO_2 concentration seems unavoidable. The combination of mitigation and adaptation can assure that the Mediterranean can continue to sustain livelihoods, provide food and protect shorelines.

MedSeA produced a short documentary entitled *'Testing the waters: Acidification in the Mediterranean'* available on the project website medsea-project.eu, and a document *"10 Facts on ocean acidification and warming in the Mediterranean Sea"*, available http://medsea-project.eu/outreach/key_documents/).

Patrizia Ziveri, ES

3.4.2 EPOCA: European Project on Ocean Acidification

The EPOCA (European Project on OCean Acidification) was launched in June 2008 for four years with the overall goal to advance our understanding of the biological, ecological, biogeochemical, and societal implications of ocean acidification. The project involved over 160 scientists from 32 institutes in ten European countries and was coordinated by Jean Pierre Gattuso (Fr). EPOCA ended in 2012. http://www.epoca-project.eu/

3.4.3 CarboChange

CarboChange is a FP7 programme focusing on the ocean carbon cycle. The project started in March 2011 and will end in February 2015, it has a budget of €7 million and 29 partners. The project focuses on observational and modelling studies on the perturbation to the ocean carbonate cycle due to the input of anthropogenic carbon. It does not explicitly deal with ocean acidification, and the effects of OA or marine ecosystems, but the efforts by CarboChange has contributed to the knowledge of changes in pH in the ocean, and for projections into the future. Important products from CarboChange include GLODAPv2 and SOCAT. http://carbochange.b.uib.no/

Toste Tanhua, DE

3.5 Other initiatives

SGOA also identified a number of other international initiatives where further potential linkages may be possible:

- **Ocean Acidification International Coordination Centre (OA-ICC)** hosted by the International Atomic Energy Authority (IAEA) works to promote, facilitate and communicate global activities on ocean acidification. The project works to communicate, promote and facilitate a series of over-arching activities in science, capacity building and communication intended to serve the scientific community, policy-makers, the general public, media and other stakeholders.
- **The OA-international Reference User Group** (OA-iRUG) is a forum, closely linked to the OA-ICC, that brings together stakeholders and scientists to disseminate the science of OA to non-technical audiences; http://www.iaea.org/ocean-acidification
- **Global Ocean Acidification Observing Network (GOA-ON):** See Section 6.2 for more information.

- **IMBER (Integrated Marine Biochemistry and Ecosystem Response)** an international coordination initiative on global environmental change, with focus on marine biogeochemical cycles, ecosystem sensitivity to global change, and predicting ocean responses. The IMBER Open Science Conference that was held in Bergen on 23–27 June 2014 included a number of OA-relevant sessions. http://www.imber.info/index.php
- The **Integrated Carbon Observing System (ICOS)** is an EU initiative that is currently in the transitional phase between the preparatory project and a European Research Infrastructure Consortium. The aim of ICOS is to provide harmonized high precision data for advanced research on the carbon cycle and greenhouse gas budgets. An Ocean Thematic Centre is being established, alongside the atmospheric and terrestrial thematic centres, jointly by the UK and Norway; participation in ICOS and the OTC is by subscription. http://www.icos-infrastructure.eu.
- **Future Earth**, a new ten year international research initiative to develop the knowledge for responding to the risks and opportunities of global environmental change, integrating existing global change programmes and projects. http://www.icsu.org/future-earth/

3.6 References

Baggini C., Salomidi M., Voutsinas E., Bray L., Krasakopoulou E., Hall-Spencer J.M. 2014. Seasonality affects macroalgal community response to increases in pCO2, PLoS ONE, 9(9), e106520, doi:10.1371/journal.pone.0106520.

Bramanti L., Movilla, J., Guron M., Calvo E., Gori A., Dominguez-Carrió C., Grinyó J., Lopez-Sanz A., Martinez-Quintana A., Pelejero C., Ziveri P., Rossi S. 2013. Detrimental effects of Ocean Acidification on the economically important Mediterranean red coral (*Corallium rubrum*), Global Change Biology, 19, (6): 1897–1908.

CBD. 2014. Decisions on Marine and Coastal Biodiversity (Agenda item 21) at 12th Conference of Parties of the Convention on Biological Diversity: UNEP/CBD/COP/12/L online via http://www.cbd.int/doc/?meeting=cop-12.

Gazeau, F., Alliouane, S., Bock, C., Bramanti, L., López Correa, M., Gentile, M., Hirse, T., Pörtner, H.-O., Ziveri, P. 2014. Impact of ocean acidification and warming on the Mediterranean mussel (*Mytilus galloprovincialis*), Front. Mar. Sci. 1:62. doi: 10.3389/fmars.2014.00062.

Ghermandi A., Galil B., Gowdy J., Nunes P.A.L.D. 2014. Jellyfish outbreak impacts on recreation in the Mediterranean Sea: welfare estimates from a socioeconomic pilot survey in Israel, Ecosystem Services, doi:10.1016/j.ecoser.2014.12.004.

Meier S., Beaufort L., Heussner S., Ziveri P. 2014. Thinning coccoliths due to ocean acidification and warming in the Mediterranean Sea, Biogeoscience. 11: 2857–2869.

Milazzo M., Rodolfo-Metalpa R., Chan V.B.S, Fine M., Alessi C., Thiyagarajan V., Hall-Spencer J.M., Chemello R., 2014. Ocean acidification impairs vermetid reef recruitment, Scientific Reports, 4: 4189, doi: 10.1038/srep04189.

Orr J. 2011. Recent and future changes in ocean carbonate chemistry. In: Gattuso J., Hansson L., editors. Ocean Acidification. New York, NY: Oxford University Press. pp. 41–66.

Rodolfo-Metalpa R., Houlbreque F., Tambutte E., Boisson F., Baggini C., Patti F.P., Jeffree R., Fine M., Foggo A., Gattuso J.-P., Hall-Spencer .J.M. 2011. Coral and mollusc resistance to ocean acidification adversely affected by warming, Nature Climate Change, 1(6): 308-312, doi: 10.1038/nclimate1200.

Rodrigues L.C., van den Bergh J.C., Ghermandi A. 2013. Socio-economic impacts of ocean acidification in the Mediterranean Sea, Marine Policy, 38: 447–456, doi: 10.1016/j.marpol.2012.07.005.

Taylor J.D., Ellis R., Milazzo M., Hall-Spencer J.M., Cunliffe M. 2014. Intertidal epilithic bacteria diversity changes along a naturally occurring carbon dioxide and pH gradient, Microbiology Ecology, 89(3): 670–678, doi: 10.1111/1574-6941.12368.

Rodrigues LC, van den Bergh J., Massa F., Theodorou J.A. Ziveri P. Gazeau P. In review. Sensitivity of Mediterranean Bivalve Mollusc Aquaculture to Climate Change, Ocean Acidification and Other Environmental Pressures: Findings from a Producers' Survey.

Ziveri P., Passaro M., Incarbona A., Milazzo M., Rodolfo-Metalpa R., Hall-Spencer J.M. 2014: Decline in coccolithophores diversity and impact on coccolith morphogenesis along a natural CO_2 gradient, The Biological Bulletin, 226: 282–290.

Secretariat of the Convention on Biological Diversity. 2009. Scientific Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity. CBD Montreal, Technical Series 46: 61 p.

Secretariat of the Convention on Biological Diversity. 2014. An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity (Eds: S. Hennige, J.M. Murray, P. Williamson). CBD Montreal, Technical Series 75: 99 p.

4 ToR C: Finalize guidelines for measuring carbonate system

The SGOA 2012 finalised JAMP Technical Guidelines, as initially drafted by the Marine Chemistry Working Group (MCWG). These have now been adopted by OSPAR and are available from the OSPAR website http://www.ospar.org/documents/dbase/decrecs/agreements/14-03e_jamp_oa_guidelines.doc. These guidelines support the monitoring of OA parameters as included in the OSPAR Coordinated Environmental Monitoring Programme (CEMP) Agreement, Appendix 16 (OSPAR 2014).

5 ToR D: Collect and exchange information on biological effects [of ocean acidification] on plankton, and macrozoobenthos

5.1 Overview of current state of knowledge of ecological impacts (key recent publications)

Although the topic area is relatively new, a substantial body of literature already exists on the potential biological effects of ocean acidification. This is a highly active area of research that is producing new publications with high frequency (>200 per annum; Gattuso and Hansson, 2011). It should be noted here that the taxonomic scope of ToR D ("… on plankton, and macrozoobenthos") seems unnecessarily restrictive, since a much wider range of marine organisms are potentially directly impacted, both negatively and positively, with others indirectly affected through interspecific interactions, affecting ecosystem function and ecosystem services.

A summary of the sensitivity of major marine groups to pH and associated carbonate chemistry parameters has been synthesized by the Intergovernmental Panel on Climate Change (IPCC); this information has been reproduced here as Table 1 and is also presented in Section 5.4. Although broad differences in sensitivity to OA are apparent, measured responses can show high variability at both inter- and intraspecific levels (Kroeker *et al.*, 2010; Barry *et al.*, 2011; Riebesell and Tortell, 2011; Wicks and Roberts, 2012). This variability is partly due to different experimental manipulations of different carbonate chemistry parameters (increased dissolved CO_2; increased H^+/ decreased pH; decreased CO_3^{2-}; increased HCO_3^-), and partly due to biological factors; thus response may vary markedly according to life stages, duration of experiment, food availability (for animals), nutrient availability (for phytoplankton, macroalgae and seagrasses), temperature, and genetic strain.

Because of the rapid developments in this field, and complexity of the interactions of OA with other factors, it would be a major undertaking for this Study Group to undertake a comprehensive and up-to-date literature review and synthesis of all potentially relevant direct and indirect effects of OA on marine organisms. The numbers of published studies on the potential impacts of OA on marine organisms continue to increase each year. While it is not the intention of this document to provide a comprehensive list or review of the recent literature, readers are directed to recent reviews on the subject (Andersson *et al.*, 2011; Barry *et al.*, 2011; Byrne, 2011; Byrne and Przeslawski, 2013; Dupont *et al.*, 2010; Gazeau *et al.*, 2013; Harvey *et al.*, 2013; Hendriks *et al.*, 2010; Hofmann *et al.*, 2010; Koch *et al.*, 2013; Kroeker *et al.*, 2010, 2013; Pörtner *et al.*, 2011; Riebesell and Tortell, 2011; Ross *et al.*, 2011; Weinbauer *et al.*, 2011). Furthermore, there are a number of summary reports on OA impacts by reputable bodies and organizations that are in progress, planned or have recently been completed, and that together provide a relatively thorough overview of the current state of knowledge in this area. As discussed elsewhere in this report, these include:

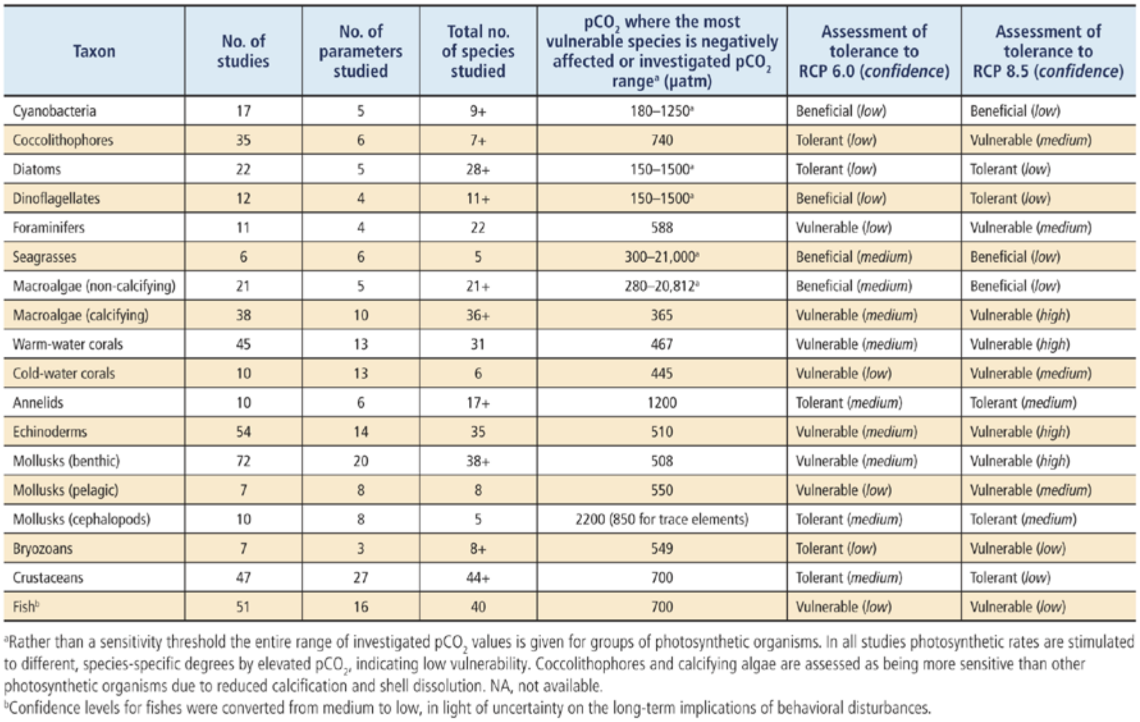
- the Arctic Ocean Acidification Assessment, by the Arctic Council's Arctic Monitoring and Assessment Programme (AMAP, 2013);
- Working Group II (Chapters 5, 6, 19 and 30) of the 5th Assessment of the Intergovernmental Panel on Climate Change (IPCC, 2014);

- an updated synthesis of OA impacts on marine organisms and systems carried out by the Convention on Biological Diversity (CBD, 2014).

Also:

- a report from the 2nd International Workshop on Ocean Acidification Impacts on Fisheries, Aquaculture, Economics and Industry held in Monaco, Nov 11–13, 2012, which examined impacts by FAO fishing areas http://www.iaea.org/ocean-acidification/page.php?page=2229;
- the Washington State Blue Ribbon Panel Report on Ocean Acidification (Adelsman and Whitely Binder, 2012), which focuses on impacts on mariculture and fisheries in the NE Pacific.

Table 1. Tolerances to ocean acidification in marine taxa, assessed from laboratory and field studies of species in the pCO_2 range from <650 to >10 000 μatm, compared to present day atmospheric levels of 400 μatm. (It should be noted that anthropogenic CO_2 emissions add to the natural variability of CO_2 concentrations in marine environments, which can reach much higher than atmospheric levels). Variables studied include growth, survival, calcification, metabolic rate, immune response, development, abundance, behaviour and others. Neither all life stages, nor all variables, including the entire range of CO_2 concentrations, were studied in all species. Confidence is based on the number of studies, the number of species studied and the agreement of results within one group. +: denotes that possibly more species or strains (genetically distinct populations of the same species) were studied, as only genus or family were specified; beneficial: most species were positively affected; vulnerable: more than 5% of species in a group will be negatively affected by 2100; tolerant: more than 95% of species will not be affected by 2100. RCP 6.0: representative concentration pathway with projected atmospheric pCO_2 = 670 μatm; RCP 8.5: pCO_2 = 936 μatm in 2100 (Meinshausen *et al.*, 2011). Confidence is limited by the short- to medium-term nature of various studies and the lack of sensitivity estimates on evolutionary time-scales, i.e. across generations (see separate reference list, online supplementary material). Note that the assessment of variability between species from the same animal phylum has revealed an increase in the fraction of sensitive species with rising CO_2 levels. (Reproduced from Table 6_2 IPCC, 2014).



Taxon	No. of studies	No. of parameters studied	Total no. of species studied	pCO_2 where the most vulnerable species is negatively affected or investigated pCO_2 range[a] (μatm)	Assessment of tolerance to RCP 6.0 (*confidence*)	Assessment of tolerance to RCP 8.5 (*confidence*)
Cyanobacteria	17	5	9+	180–1250[a]	Beneficial (*low*)	Beneficial (*low*)
Coccolithophores	35	6	7+	740	Tolerant (*low*)	Vulnerable (*medium*)
Diatoms	22	5	28+	150–1500[a]	Tolerant (*low*)	Tolerant (*low*)
Dinoflagellates	12	4	11+	150–1500[a]	Beneficial (*low*)	Tolerant (*low*)
Foraminifers	11	4	22	588	Vulnerable (*low*)	Vulnerable (*medium*)
Seagrasses	6	6	5	300–21,000[a]	Beneficial (*medium*)	Beneficial (*low*)
Macroalgae (non-calcifying)	21	5	21+	280–20,812[a]	Beneficial (*medium*)	Beneficial (*low*)
Macroalgae (calcifying)	38	10	36+	365	Vulnerable (*medium*)	Vulnerable (*high*)
Warm-water corals	45	13	31	467	Vulnerable (*medium*)	Vulnerable (*high*)
Cold-water corals	10	13	6	445	Vulnerable (*low*)	Vulnerable (*medium*)
Annelids	10	6	17+	1200	Tolerant (*medium*)	Tolerant (*medium*)
Echinoderms	54	14	35	510	Vulnerable (*medium*)	Vulnerable (*high*)
Mollusks (benthic)	72	20	38+	508	Vulnerable (*medium*)	Vulnerable (*high*)
Mollusks (pelagic)	7	8	8	550	Vulnerable (*low*)	Vulnerable (*medium*)
Mollusks (cephalopods)	10	8	5	2200 (850 for trace elements)	Tolerant (*medium*)	Tolerant (*medium*)
Bryozoans	7	3	8+	549	Tolerant (*low*)	Vulnerable (*low*)
Crustaceans	47	27	44+	700	Tolerant (*medium*)	Tolerant (*low*)
Fish[b]	51	16	40	700	Vulnerable (*low*)	Vulnerable (*low*)

[a] Rather than a sensitivity threshold the entire range of investigated pCO_2 values is given for groups of photosynthetic organisms. In all studies photosynthetic rates are stimulated to different, species-specific degrees by elevated pCO_2, indicating low vulnerability. Coccolithophores and calcifying algae are assessed as being more sensitive than other photosynthetic organisms due to reduced calcification and shell dissolution. NA, not available.

[b] Confidence levels for fishes were converted from medium to low, in light of uncertainty on the long-term implications of behavioral disturbances.

5.2 Ocean Acidification and cold-water corals

5.2.1 Cold-water corals in a changing ocean

The functional ecology of cold-water coral (CWC) ecosystems is not well-understood, despite their global distribution. Here we focus on the reef frameworks built by a small group of scleractinian CWCs, in particularly *Lophelia pertusa* since this species dominates CWC reefs and mounds in the OSPAR area. These CWC structures are now known to be rich in local biodiversity and important in the life cycles of certain deep-water fish, although our understanding of these relationships remains poorly developed. CWCs appear sensitive to even small changes in seawater temperature, and the fossil record shows how each major extinction event of previous coral fauna was strongly related to perturbations in the ocean's carbon cycle. This sensitivity to geological periods of carbon cycle change underpins our present understanding of the sensitivity of CWCs to anthropogenic ocean acidification. Although there is clear evidence of prior periods of ocean acidification, both the magnitude and rate of CO_2 release in geological history are far lower than the present day. Scientific understanding of the impacts of ocean acidification (OA) on CWCs is here summarized around three overarching aims: (1) understanding global patterns of OA; (2) understanding ecosystem response; (3) providing data necessary to optimize modelling, each aim derived from the goals set by the developing Global OA Observation Network. In summary:

Aim 1. Global OA condition: CWCs provide a valuable new archive of intermediate water mass history with boron isotopes in coral carbonate a potentially important new pH proxy derived from fossil coral skeletons that can be precisely dated.

Aim 2. Ecosystem response: Global ocean modelling predicts rapid shoaling of the aragonite saturation horizon that would expose most CWCs to corrosive seawater by the end of the 21st century. Experimental work to examine CWC response to OA has begun. Early studies show evidence of declining growth over relatively short time periods, but did not factor temperature increase into experimental design. More recently temperature has been included, experimental periods have increased and effects on coral skeletal structure have been examined.

Aim 3. Providing data to optimize modelling: There has been increased effort made in characterizing the dynamics of carbonate chemistry around CWC sites with work at the Mingulay Reef Complex (NE Atlantic) showing up to 0.1 pH unit shifts associated with tidal downwelling. Predictive habitat suitability modelling shows the importance of aragonite saturation state as a key variable in controlling CWC distribution with recent studies employing increased resolution environmental data. The importance of water mass in controlling CWC occurrence was reviewed with a focus on the Hebrides Terrace Seamount where framework-forming CWCs were present at low aragonite saturation states (at times <1), but the species present was different from that at shallower depths. Further work is clearly needed to fully understand the factors controlling CWC distribution, and the need for long-term *in situ* environmental datasets, repeat surveys and work to track changes in community ecology over time were all highlighted.

J Murray Roberts (Heriot-Watt University)

5.2.2 KnowSeas Project

The EU FP7 Knowledge-based Sustainable Management for Europe's Seas (KnowSeas) used a DPSIR (Driver, Pressure, State, Impact and Response) framework to review the current science to identify the key ecosystem services provided by deep-water coral reefs and the drivers and pressures on the habitat (endogenic managed and exogenic unmanaged). Data were collated on coral distribution and the distribution of aragonitic reefs was modelled to determine whether existing protection of deep-water coral reefs would be fit for future purpose (including meeting GES targets) in the face of ocean acidification, and if not what steps may need to be considered in order to ensure the protection of this habitat (Figure 13).

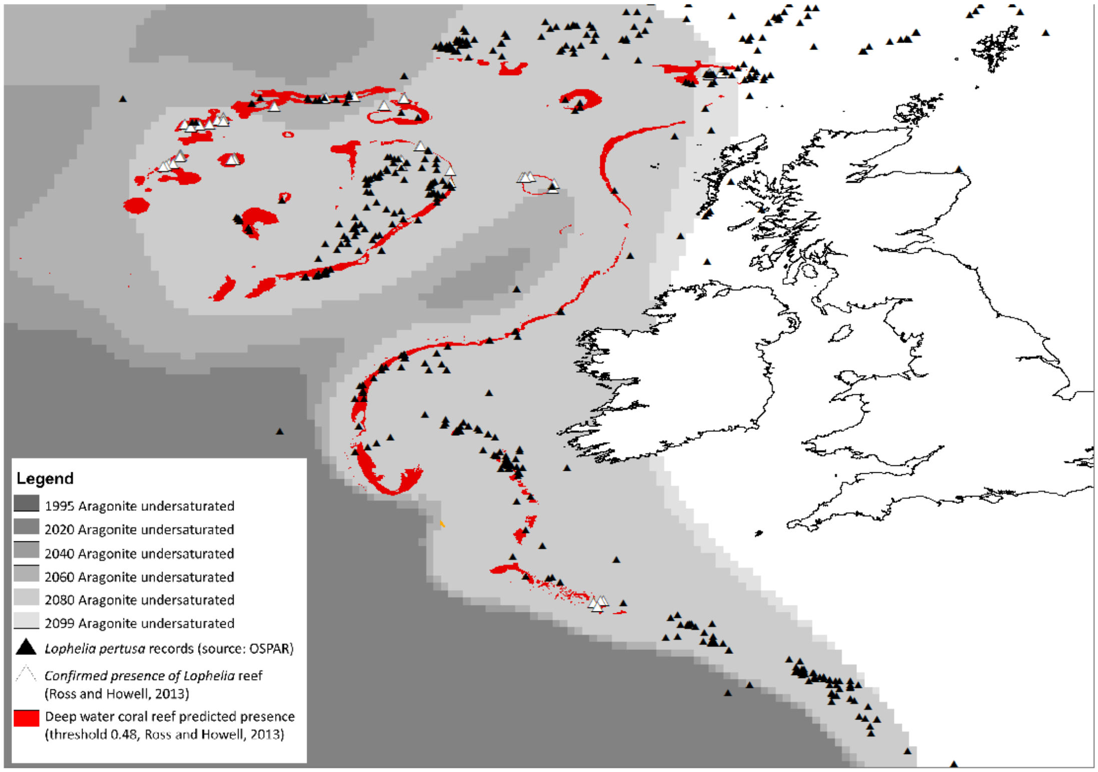


Figure 13. Aragonite saturation horizon shoaling for 2020, 2040, 2060, 2080 and 2099. Stony coral records (MESH database) and predicted aragonitic reef extent (from Jackson *et al.*, 2014).

The KnowSeas project ended in June 2013 and has been published: Jackson *et al.*, (2014).

Jason Hall-Spencer (Plymouth University)

5.3 Ecological effects of acidification around marine CO_2 vents

Laboratory and mesocosm research into ocean acidification has been augmented in recent years with work at volcanic vents which show which organisms can survive elevated CO_2 levels and what communities of organisms are like after chronic exposure to low carbonate saturation states. Initial work described obvious ecological shifts in rock and seagrass habitats along gradients in carbonate chemistry in the Mediterranean with major losses of calcareous organisms below mean pH 7.8 (Hall-Spencer *et al.*, 2008; Martin *et al.*, 2008). There has since been improved pH monitoring at these sites (Kerrison *et al.*, 2011) and assessments of fundamental processes such as calcification and the ways in which acidification lowers the diversity of communities of seaweeds, sponges and in sediments (Hahn *et al.*, 2012; Dias *et al.*, 2010; Porzio *et al.*, 2011; Goodwin *et al.*, 2013). The vents are useful for studies of invertebrate recruitment revealing that juvenile bivalves are especially vulnerable (Cigliano *et al.*, 2010) and can be used to demonstrate how community interactions alter as CO_2 levels increase (Kroeker *et al.*, 2012). Transplantations (of bryozoans, corals, molluscs) show which organisms can adapt to chronic exposure to elevated CO_2 and the extent to which warming exacerbates the effects of OA (Rodolfo-Metalpa *et al.*, 2010; Rodolfo-Metalpa *et al.*, 2011; Rodolfo-Metalpa *et al.*, 2015).

Collaborations with scientists at vents in Italy, Greece, Mexico and Papua New Guinea show that marine systems respond in predictable ways to increased CO_2, although confounding factors such as variations in alkalinity or toxic metals need to be avoided (Boatta *et al.*, 2013). Observations off Sicily reveal that OA is likely to cause significant microbial community shifts (Johnson *et al.*, 2011; Lidbury *et al.*, 2012; Pettit *et al.*, 2013) to alter plant defence chemicals that act as grazing deterrents (Arnold *et al.*, 2012) to benefit anemones, and corrode calcified organisms such as corals (Suggett *et al.*, 2012). The ability to adapt physiologically and genetically to acidification at the vents varies in closely related species (Calosi *et al.*, 2013a; Calosi *et al.*, 2013b).

Taken as a whole these results indicate that, within the OSPAR region, aragonitic deep-water reefs formed by species such as *Lophelia pertusa* are likely to dissolve if saturation state is greatly lowered, as are high magnesium-calcite maerl beds formed by species such as *Lithothamnion glaciale*. Seagrasses and invasive seaweeds can be expected to proliferate although the biodiversity of seagrass habitats is expected to decline. Given that NE Atlantic coastal waters have high food availability, commercially important shellfish such as oysters and mussels may not be as vulnerable to ocean acidification as those found in oligotrophic waters. The worldwide occurrence of marine CO_2 vent systems strengthens predictions about the effects of ocean acidification that can be applied at the ecosystem scale to all areas, including the NE Atlantic (Johnson *et al.*, 2012; Russell *et al.*, 2013).

5.4 Climate change impacts on the world's oceans: A sectoral analysis by IPCC AR5

The accumulation of CO_2 in ocean surface waters disturbs water chemistry and causes acidification. The author team of IPCC Working Group II, chapter 6 (Pörtner *et al.*, 2014), has assessed present knowledge for ocean systems, their natural components and the associated human and economic interests and developed the following consensus statement with respect to ocean acidification:

"Rising atmospheric CO_2 over the last century and into the future not only causes ocean warming but also changes carbonate chemistry in a process termed ocean acidification (WGI AR5 Sections 3.8.2, 6.4.4). Impacts of ocean acidification range from changes in organismal physiology and behaviour to population dynamics (*medium* to *high confidence*) and will affect marine ecosystems for centuries if emissions continue (*high confidence*). Laboratory and field experiments as well as field observations show a wide range of sensitivities and responses within and across organism phyla (*high confidence*). Most plants and microalgae respond positively to elevated CO_2 levels by increasing photosynthesis and growth (*high confidence*). Within other organism groups, vulnerability decreases with increasing capacity to compensate for elevated internal CO_2 concentration and falling pH (*low* to *medium confidence*). Among vulnerable groups sustaining fisheries, highly calcified corals, molluscs, and echinoderms are more sensitive than crustaceans (*high confidence*) and fishes (*low confidence*). Trans-generational or evolutionary adaptation has been shown in some species, reducing impacts of projected scenarios (*low* to *medium confidence*). Limits to adaptive capacity exist but remain largely unexplored." (Also see Section 5.1 Table 1).

5.5 References

Adelsmann, H. and Whitely Binder, L. (2012) Washington State Blue Ribbon Panel on Ocean Acidification: Ocean Acidification: From Knowledge to Action, Washington State's Strategic Response. H. Adelsman and L. Whitely Binder (eds). Washington Department of Ecology, Olympia, Washington. Publication no. 12-01-015.

AMAP. 2013. AMAP Assessment 2013: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. viii + 99 pp.

Andersson, A.J., Mackenzie, F.T. and Gattuso, J.-P. 2011. Chapter 7. Effects of ocean acidification on benthic processes, organisms, and ecosystems. pp. 122–153. In Gattuso, J.-P., and L. Hansson (Eds.). Ocean Acidification. Oxford University Press.

Arnold, T., Mealey, C., Leahey, H., Whitman Miller, A., Hall-Spencer, JM., Milazzo, M. and Maers, K. 2012. Ocean acidification and the loss of protective phenolics in seagrasses. PLoS ONE 7(4): e35107.

Barry, J.P., Widdicombe, S. and Hall-Spencer, J.M. 2011. Effects of ocean acidification on marine biodiversity and ecosystem function. pp. 192–209. In, Gattuso, J.-P., and L. Hansson (Eds.). Ocean Acidification. Oxford University Press.

Boatta, F., D'Alessandro, W., Gagliano, A.L., Liotta, M., Milazzo, M., Rodolfo-Metalpa, R., Hall-Spencer, J.M. and Parello, F. 2013. Geochemical survey of Levante Bay, Vulcano Island (Italy) and its suitability as a natural laboratory for the study of ocean acidification. Marine Pollution Bulletin 73: 485–494.

Byrne, M. 2011. Impact of ocean warming and ocean acidification on marine invertebrate life history stages: vulnerabilities and potential for persistence in a changing ocean. Oceanography and Marine Biology: An Annual Review, 49: 1–42.

Byrne, M. and Przeslawski, R. 2013. Multistressor impacts of warming and acidification of the ocean on marine invertebrates' life histories. Integrative Comparative Biology, 53: 582–596. doi:10.1093/icb/ict049

Calosi, P., Rastrick, S.P.S., Graziano, M., Thomas, S.C., Baggini, C., Carter, H.A., Hall-Spencer, J.M., Milazzo, M. and Spicer, J.I. 2013a. Acid-base and ion-regulation capacity-dependent distribution of sea urchins living near shallow water CO_2 vents. Marine Pollution Bulletin 73: 470–484.

Calosi, P., Rastrick, S.P.S., Lombardi, C., de Guzman, H.J., Davidson, L., Jahnke. M., Gambi, M.C. 2013b. Adaption and acclimatization to ocean acidification in marine ecotherms: an *in situ* transplant experiment with polychaetes at a shallow CO_2 vent system. Phil Trans Roy Soc 368, 20120444.

Cigliano, M., Gambi, M.C., Rodolfo-Metalpa, R., Patti, F.P. and Hall-Spencer, J.M. 2010. Effects of ocean acidification on invertebrate settlement. Marine Biology 157: 2489–2502.

Dias, B., Hart, M.B., Smart, C.W. and Hall-Spencer, J.M. 2010. Modern seawater acidification: the response of foraminifers to high-CO_2 conditions in the Mediterranean Sea. Journal of the Geological Society, London 167: 843–846.

Dupont, S., Ortega-Martinez, O., and Thorndyke, M. 2010. Impact of near-future ocean acidification on echinoderms. Ecotoxicology, 19: 449–462. doi. 10.1007/s10646-010-0463-6.

Gattuso J.-P. and Hansson L. 2011. Ocean acidification, 352 p. Oxford: Oxford University Press.

Gazeau, F., Parker, L.M., Comeau, S., Gattuso, J.-P., O'Connor, W.A., Martin, S., Pörtner, H.-O., and Ross, P.M. 2013. Impacts of ocean acidification on marine shelled molluscs. Marine Biology, 160:2207–2245. DOI 10.1007/s00227-013-2219-3.

Goodwin, C., Rodolfo-Metalpa, R., Picton, B. and Hall-Spencer, J.M. 2013. Effects of ocean acidification on sponge communities. Marine Ecology, 2013: 1–9.

Hahn, S., Rodolfo-Metalpa, R., Griesshaber, E., Schmahl, W. W., Buhl, D., Hall-Spencer, J. M., Baggini, C., Fehr, K. T., and Immenhauser, A. 2012. Marine bivalve shell geochemistry and ultrastructure from modern low pH environments: environmental effect versus experimental bias. Biogeosciences 9: 1897–1914.

Hall-Spencer, J.M., Rodolfo-Metalpa, R., Martin, S., Ransome, E., Fine, M., Turner, S.M., Rowley, S.J., Tedesco, D. and Buia M.C. 2008. Volcanic carbon dioxide vents reveal ecosystem effects of ocean acidification. Nature 454: 96–99.

Harvey, B.P., Gwynn-Jones, D., and Moore, P.J. 2013. Meta-analysis reveals complex marine biological responses to the interactive effects of ocean acidification and warming. Ecology and Evolution, 3:1016–1030. DOI: 10.1002/ece3.516.

Hendriks, I.E., Duarte, C.M., and Álvarez, M. 2010. Vulnerability of marine biodiversity to ocean acidification: A meta-analysis. Estuarine, Coastal and Shelf Science, 86:157–164. http://dx.doi.org/10.1016/j.ecss.2009.11.022.

Hofmann, G.E., Barry, J.P., Edmunds, P.J., Gates, R.D., Hutchins, D.A., Klinger, T. and Sewell, M.A. 2010. The effect of ocean acidification on calcifying organisms in marine ecosystems: an organism-to-ecosystem perspective. Annual Review of Ecology, Evolution, and Systematics, Vol. 41: 127–147.

IPCC, 2014: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

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

Johnson, V.R., Brownlee, C. Rickaby, R.E.M., Graziano, M., Milazzo, M. and Hall-Spencer, J.M. 2011. Responses of marine benthic microalgae to elevated CO_2. Marine Biology. 160: 1813–1824.

Johnson, V.R., Russell, B.D., Fabricius, K.E., Brownlee, C. and Hall-Spencer, J.M. 2012. Temperate and tropical brown macroalgae thrive, despite decalcification, along natural CO_2 gradients. Global Change Biology. 18: 2792–2803.

Kerrison, P., Hall-Spencer, J., Suggett, D.J., Hepburn, L.J. and Steinke, M. 2011. Assessment of pH variability at coastal CO_2 vents for ocean acidification studies. Estuarine, Coastal and Shelf Science 94: 129–137.

Koch, M., Bowes, G., Ross, C. and Zhang, X.-H. 2013. Climate change and ocean acidification effects on seagrasses and marine macroalgae. Global Change Biology, 19: 103–132. doi: 10.1111/j.1365-2486.2012.02791.x.

Kroeker, K. J., Kordas, R. L., Crim, R. N. and Singh, G. G. 2010. Meta-analysis reveals negative yet variable effects of ocean acidification on marine organisms. Ecology Letters, 13: 1419–1434. doi: 10.1111/j.1461-0248.2010.01518.x.

Kroeker, K.J., Micheli, F., and Gambi, M.C. 2012. Ocean acidification causes ecosystem shifts via altered competitive interactions. Nature Climate Change 3: 156–159.

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

Lidbury, I., Johnson, V., Hall-Spencer, J., Munn, C.B., and Cunliffe, M. 2012. Community-level response of coastal microbial biofilms to ocean acidification in a natural carbon dioxide vent ecosystem. Marine Pollution Bulletin 64: 1063–1066.

Martin, S., Rodolfo-Metalpa, R., Ransome, E., Rowley, S., Buia, M.C., Gattuso, J.P. and Hall-Spencer, J. 2008. Effects of naturally acidified seawater on seagrass calcareous epibionts. Biology Letters 4: 689–692.

Meinshausen, M., Smith, S.J., Calvin, K., Daniel, J.S., Kainuma, M.L.T., Lamarque, J.F., Matsumoto, K., Montzka, S.A. Raper, S.C.B. Riahi, K., Thomson, A., Velders, G.J.M. and van Vuuren, D.P.P. 2011. The RCP greenhouse gas concentrations and their extensions from 1765 to 2300. Climatic Change, 109: 213–241.

Pettit, L.R., Hart, M.B., Medina-Sánchez, A.N., Smart, C.W., Rodolfo-Metalpa, R., Hall-Spencer, J.M. and Prol-Ledesma, R.M. 2013. Benthic foraminifera show some resilience to ocean acidification in the northern Gulf of California, Mexico. Marine Pollution Bulletin, 73: 452–462.

Pörtner, H.-O., Karl, D.M., Boyd, P.W., Cheung, W.W.L., Lluch-Cota, S.E., Nojiri, Y. Schmidt, D.N. and Zavialov, P.O. 2014: Ocean systems. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change [Field, C.B., V.R. Barros, D.J. Dokken, K.J. Mach, M.D. Mastrandrea, T.E. Bilir, M. Chatterjee, K.L. Ebi, Y.O. Estrada, R.C. Genova, B. Girma, E.S. Kissel, A.N. Levy, S. MacCracken, P.R. Mastrandrea, and L.L. White (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA, pp. 411–484. https://ipcc-wg2.gov/AR5/images/uploads/WGIIAR5-Chap6_FINAL.pdf.

Pörtner, H.-O., Gutowska, M., Ishimatsu, A. Lucassen, M. Melzner, F., and Seibel, B. 2011. Effects of ocean acidification on nektonic organisms. pp. 154–175. In, Gattuso, J.-P., and L. Hansson (Eds.). Ocean Acidification. Oxford University Press.

Porzio L. Buia, M.C., Spencer-Hall, J.M. 2011. Effects of ocean acidification on macroalgal communities. Journal of Experimental Marine Biology and Ecology, 400: 278–287.

Riebesell, U. and Tortell, P.D. 2011. Chapter 6. Effects of ocean acidification on pelagic organisms and ecosystems. pp. 99–121. In, Gattuso, J.-P., and L. Hansson (Eds.). Ocean Acidification. Oxford University Press.

Rodolfo-Metalpa, R., Houlbreque, F., Tambutte, E., Boisson, F., Baggini, C., Patti, F.P., Jeffree, R., Fine, M., Foggo, A., Gattuso, J.P. and Hall-Spencer, J. M. 2011. Coral and mollusc resistance to ocean acidification adversely affected by warming. Nature Climate Change, 1: 308–312.

Rodolfo-Metalpa, R., Lombardi, C., Cocito, S., Hall-Spencer, J. M. and Gambi, M. C. 2010. Effects of ocean acidification and high temperatures on the bryozoan *Myriapora truncata* at natural CO_2 vents. Marine Ecology, 31: 447–456.

Rodolfo-Metalpa, R., Montagna, P., Aliani, S., Borghini, M., Canese, S., Hall-Spencer, J. M., Foggo, A., *et al.* 2015. Calcification is not the Achilles' heel of cold-water corals in an acidifying ocean. Global Change Biology: DOI: 10.1111/gcb.12867.Ross P.M., Parker L., O'Connor W.A., and Bailey E.A. 2011. The impact of ocean acidification on reproduction, early development and settlement of marine organisms. Water, 3:1005–1030.

Russell, B.D., Connell, S.D., Uthicke, S., Muehllehner, N., Fabricius, K.E. and Hall-Spencer, J.M. 2013. Future seagrass beds: increased productivity leading to carbon storage? Marine Pollution Bulletin, 73: 463–469.

Secretariat of the Convention on Biological Diversity. 2014. An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity. (Eds: S. Hennige, J.M. Roberts and P. Williamson). Montreal, Technical Series No. 75: 99p.

Suggett, D.J., Hall-Spencer, J.M., Rodolfo-Metalpa, R., Boatman, T.G., Payton, R., Pettay, D.T., Johnson, V.R., Warner, M.E. and Lawson, T. 2012 Sea anemones may thrive in a high CO_2 world. Global Change Biology, 18: 3015–3025.

Weinbauer, M.G., Mari, X., and Gattuso, J.-P. 2011. Chapter 5. Effects of ocean acidification on the diversity and activity of heterotrophic marine microorganisms. pp. 83–98. In, Gattuso, J.-P., and L. Hansson (Eds.). Ocean Acidification. Oxford University Press.

Wicks, L.C., and Roberts, J.M. 2012. Benthic invertebrates in a high CO_2 world, Oceanography and Marine Biology: An Annual Review, 50 (2012), pp. 127–188.

6 ToR E: Consider the strategy that would be required for an assessment framework appropriate to long-term assessment of the intensity/severity of the effects of ocean acidification, including any assessment criteria required

6.1 Background

Ocean acidification monitoring (OA carbonate parameters) is currently in the "pre-CEMP" (Appendix 16) section of the OSPAR Coordinated Environmental Monitoring Programme (CEMP) implying voluntary monitoring by OSPAR Contracting Parties (CPs). To address the above ToR SGOA 2012 proposed to OSPAR that SGOA would elaborate a high-level common monitoring and assessment strategy for consideration by OSPAR. This proposal was endorsed by OSPAR CoG 2013 and SGOA elaborated the strategy during the 2013/2014 meetings.

SGOA also recognized that monitoring in the OSPAR region should be coherent with other regional and global monitoring activities. **A US Strategic Plan for Federal Research and Monitoring of OA** has been developed. Furthermore, a **Global OA Observing Network (GOA-ON)** is developing a global approach to OA monitoring. It is essential that OA monitoring conducted in the Northeast Atlantic, under the umbrella of OSPAR, is well aligned with approaches of the US and Canada to ensure a coherent datasets are generated for the North Atlantic. Moreover, such monitoring should take cognisance of, and contribute to, the global effort as outlined by GOA-ON. These initiatives are described in the following sections.

SGOA also noted the requirement for certain EU Member States to put in place monitoring under Article 11 of the **Marine Strategy Framework Directive**[4] (MSFD). While OA is not specifically mentioned as a pressure or an element of Good Environmental Status (GES) under the MSFD and the GES Decision[5], Annex III of the MSFD does specify *pH, pCO_2 profiles or equivalent information used to measure marine acidification* as a physical and chemical characteristic to be considered in the initial assessment and monitoring. It was not clear to SGOA how OA is integrated into Member States MSFD monitoring programmes. SGOA noted that while OA is a fairly slow process evolving on decadal timescales it will still be pertinent to many GES descriptors and there are potential synergies between MSFD monitoring programmes and an OSPAR OA programme, e.g. in terms of parameters, monitoring platforms, and data management.

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[4] Directive 2008/56/EC of the European Parliament and Council of 17 June 2008 establishing a framework for community action in the field of marine environmental policy (Marine Strategy Framework Directive).

[5] Commission Decision 2010/477/EU of 1 September 2010 on criteria and methodological standards on good environmental status of marine waters.

6.2 Global Ocean Acidification Observing Network (GOA-ON)

SGOA discussions between 2012 and 2014 have occurred in parallel with the community-led development of a Global Ocean Acidification Observing Network (GOA-ON). The GOA-ON initiative arose from recognition of shared needs of the international research community, national funding agencies and intergovernmental bodies; its three main goals and overall approach are closely congruent to the SGOA framework (and vice versa), and close working links have been established and maintained.

The main sponsoring bodies of GOA-ON to date have been the Intergovernmental Oceanographic Commission (IOC) of UNESCO and its Global Ocean Observing System (GOOS, co-supported by WMO, UNEP and ICSU); the International Ocean Carbon Coordination Project (IOCCP, a joint initiative of IOC and SCOR); the Ocean Acidification International Coordination Centre (OA-ICC) and the International Atomic Energy Agency; the US National Oceanic and Atmospheric Administration (NOAA); the UK Ocean Acidification research programme (UKOA); the University of Washington; and other national bodies and agencies. A GOA-ON Executive Council has been established, also a GOA-ON website http://www.goa-on.org (hosted by the NOAA Pacific Marine Environmental Laboratory) that includes an interactive map of current OA monitoring activities.

Two international workshops have been held by GOA-ON: at Seattle in 2012, and St Andrews in 2014. Around 115 individuals were involved, from over 30 countries. A combined report was published in late 2014, detailing the network's requirements and its governance plan ("GOA-ON Plan"; Newton *et al.*, 2014).

The GOA-ON framework is provided by three goals, relating to "ocean acidification measurements for management and scientific knowledge"; specifically, to obtain information and understanding of chemical conditions and ecosystem responses, and achieve data synthesis through modelling. The GOA-ON Plan (Newton *et al.*, 2014) provides both broad concepts and key critical details on how to meet these goals. Thus it defines: the network design strategy; ecosystem and goal-specific variables; spatial and temporal coverage needs; observing platform-specific recommendations; data quality objectives and requirements; initial GOA-ON products, outcomes, and applications; GOA-ON's proposed governance structure; and network support requirements.

Two common problems have been faced by both GOA-ON and SGOA:

- Where to make the distinction between OA measurements that are considered essential (GOA-ON Level 1 observations: 'critical minimum measurements') and those that are considered highly desirable (GOA-ON Level 2: 'enhanced suite of measurements… promote understanding of mechanisms'). That distinction is necessary, but does depend, to some degree, on the expected availability of resources and technological capabilities; the intended spatial and temporal coverage; and whether the approach is inherently aspirational, targeting as much information as possible for scientific interpretation of observed variability, or inherently pragmatic (and resource-limited), with focus on a doable core suite that would be widely applicable.
- The degree of specificity for biological/ecosystem measurements, noting (particularly for GOA-ON) that they may need to be applied over a very wide

range of biogeographic regions (physical habitat types and climatic conditions).

The guidance developed by GOA-ON was taken into account by SGOA, and proved of great value. Further close contact between the OSPAR/ICES research communities and GOA-ON is therefore strongly encouraged, to include additional input to the GOA-ON interactive map. Nevertheless, it was recognised that many aspects of the GOA-ON Plan reflected 'work in progress', and that GOA-ON is necessarily wider in scope (e.g. also covering warm-water coral habitats); as a result there is not an exact match in approaches between SGOA and the GOA-ON initiative.

6.3 US Strategic Plan for Federal Research and Monitoring of OA

US congress passed the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM Act), which called on the Subcommittee on Ocean Science and Technology (SOST) to establish an Interagency Working Group on Ocean Acidification (IWG-OA; http://oceanacidification.noaa.gov/IWGOA.aspx). In line with the requirements of the Act, the IWG-OA developed a strategic research plan to guide "Federal research and monitoring on ocean acidification that will provide for an assessment of the impacts of ocean acidification on marine organisms and marine ecosystems and the development of adaption and mitigation strategies to conserve marine organisms and marine ecosystems." The plan focused on seven themes: (1) monitoring; (2) research; (3) modelling; (4) technology development; (5) socio-economic impacts; (6) education, outreach, and engagement strategies; and (7) data management and integration with recommendations and short-term (3- to 5-year) and long-term (10-year) goals (IWG-OA, 2014). Highlights of the plans research goals include:

- Improve existing observing systems that monitor chemical and biological effects of ocean acidification and document trends.
- Undertake laboratory and field research to examine the physiological, behavioural, and evolutionary adaptive capacities of selected species and complexes of species.
- Develop comprehensive models to predict changes in the ocean carbon cycle and effects on marine ecosystems and organisms.
- Develop vulnerability assessments for various CO_2 emissions scenarios.
- Assess the cultural, subsistence, and economic effects of ocean acidification.

6.4 A Proposed Common Monitoring and Assessment Strategy for OSPAR

SGOA 2013 provided OSPAR with an outline of key elements envisaged in an OSPAR Common OA Monitoring and Assessment Strategy and OSPAR Contracting Parties were invited to comment (CoG(1) 2014 Summary Record). No comments were received. The draft monitoring strategy was completed at SGOA 2014 and is presented at Annex 5 of this report. The draft is proposed as the basis for an OSPAR Agreement on harmonised monitoring and assessment of OA.

The strategy addresses the requirement for monitoring the carbonate system (spatial and temporal characteristics of acidification) and the biological/ecological impacts of OA.

However, a flexible strategy that can adapt to our rapidly evolving understanding of OA and its potential impacts, and anticipated technological developments (e.g. in the areas of sensors, modelling and data analytics) is essential. The proposed strategy sets out guiding principles and defines two goals. Broadly, these are to determine OA-related chemical conditions and trends over various spatial and temporal scales, including multidecadal time-series, (Goal 1) and the ecosystem response to OA (Goal 2). Within these two levels of measurements are defined; essential core measurements (level 1) and additional desirable parameters (level 2). This is a similar, albeit simpler, approach to GOA-ON which defined three goals (modelling is integrated into goals 1 and 2 rather than a stand-alone goal in the SGOA strategy) and three levels of measurements.

Two key challenges in implementing an OA monitoring programme are:

- achieving the data needs (in terms of data quality and adequate spatial/temporal coverage) to determine long-term trends against a background of high natural variability (the analogous concept of "climate"vs."weather" is used in GOA-ON to convey this); and,
- the development of robust, sensitive OA-specific biological indicators that are broadly applicable across a wide biogeographic region. (See Section 7).

SGOA suggests monitoring cycles to tie in with OSPAR (e.g. Quality Status Report) and MSFD cycles (~six years). The need to commence chemical monitoring at an early stage and establish a current reference against which future changes can be assessed has been previously highlighted (Hydes *et al.*, 2013) and SGOA emphasised that the initial phase of OSPAR monitoring should focus on establishing coordinated monitoring of the carbon system, including developing enhanced QA tools, to describe the current conditions and variability within the OSPAR area. Leveraging existing monitoring activities and infrastructure by adding relevant measurements of OA parameters could greatly contribute to a cost-effective and integrated approach to monitoring. Following this initial chemistry focused monitoring phase, it is proposed that an assessment be undertaken focusing on identifying the most vulnerable areas/ecosystems within the OSPAR region and this would support planning of the second cycle. For the second and subsequent cycles SGOA envisaged monitoring of OA across the entire OSPAR area (focus on Goal 1) but also prioritised and more intensive monitoring of areas identified as most vulnerable (focus on Goal 1 OA Conditions and Goal 2 Ecosystem Response considering level 1 and 2 parameters) with a tailored plan for each area identified. Notwithstanding, the Arctic Ocean is particularly sensitive to OA and is expected to show widespread calcium carbonate undersaturation conditions earlier than other oceans (Steinacher *et al.*, 2009; AMAP, 2013). Colder and fresher water means it is more susceptible to CO_2 uptake but less well buffered than temperate oceans. Other aspects contributing to this vulnerability include additional carbon sources (methane and organic carbon inputs) and the low biodiversity and simple foodwebs that characterize the Arctic.

Clearly, the Goal 2 monitoring depends on development of appropriate indicators (see Section 7). Such vulnerable areas would have one or more of the following attributes:

- More rapid rate of acidification for example driven by cold-water temperatures, freshwater input changes, low buffering capacity, specific hydrodynamics such as upwelling of CO_2-rich waters, and/or subject to other drivers of acidification such as eutrophication;

- Contain particularly susceptible ecosystems, species and/or habitats;
- A high socio-economic dependence on marine ecosystem services.

While the vulnerable areas are expected to provide earliest indications of impacts they are also a bellwether for wider scale impacts across all marine ecosystems.

In conclusion SGOA recommends that:

- the draft OSPAR Agreement on a Common Strategy to enhance Coordinated Monitoring of Ocean Acidification in the Northeast Atlantic (Annex 5) should be proposed to OSPAR for adoption to foster implementation of a flexible long-term monitoring and assessment programme in the OSPAR regions.
- OSPAR monitoring should be initiated as early as possible to ensure high quality long-term datasets can be generated. The lack of specific biological indicators at this stage should not impede development of monitoring chemical aspects of OA.
- OSPAR monitoring as it evolves should continue to ensure coherence with other regional (e.g. US and Arctic) and global OA monitoring developments to ensure data can be harmonized at a North Atlantic scale and contributes to GOA-ON vision.
- where feasible, relevant OA parameters should be routinely added to other existing and planned monitoring activities in the OSPAR area with a view to developing long-term and integrated datasets. This includes adding relevant parameters to monitoring of major river discharges.
- the Arctic should be afforded special prominence in OSPAR OA-monitoring due to its inherent vulnerability to OA.

6.5 QA/QC considerations to progress OA monitoring within OSPAR CEMP

Development of suitable QA & QC tools is critical to support harmonized monitoring and to translating OA from the OSPAR preCEMP to the mandatory CEMP. To assess accuracy of measurements, reference materials (RM) are available for TA and DIC analysis, while reference gases are available for calibration of pCO_2 systems.

For the analysis of TA and DIC, the carbonate analysis community use a reference material supply service provided by Andrew Dickson's laboratory at the Scripps Institute of Oceanography (University of California). These reference materials consist of natural seawater sterilized by a combination of filtration, ultraviolet radiation and addition of mercuric chloride. The RM is only available at one salinity and may not be applicable to all areas. SGOA echoes the views of ICES MCWG that there is concern about the available capacity to produce sufficient quantities of reference material to support the needs of an expanding monitoring community and all efforts to increase this capacity should be supported.

SGOA recommend that since carbonate parameters are now in the OSPAR pre-CEMP there is an urgent need for suitable RM's covering a range of salinities to be developed.

There is currently no routine intercalibration or proficiency testing scheme available for the carbonate chemistry parameters. There have, however been *ad hoc* intercalibration exercises organised by Andrew Dickson's laboratory, the last being in 2013. For long-term monitoring SGOA recognize there is a need for a proficiency-testing scheme for carbonate parameters, similar to that offered by QUASIMEME. QUASIMEME have a long experience in providing technical Quality Assurance support for monitoring parameters in the CEMP, however they don't have the expertise to produce materials for the carbonate system. SGOA noted discussions held between ICES MCWG and QUASIMEME in 2012/13/14 regarding the need for ongoing proficiency testing to support analysis of carbonate system parameters.

SGOA recommend that QUASIMEME should be encouraged to develop a proficiency-testing scheme for TA and DIC.

MCWG 2013 identified the need for a workshop on the comparability of sampling and analysis of Total Alkalinity (TA) and Dissolved Inorganic Carbon (DIC).

SGOA strongly agreed that such a workshop is essential to progress coordinated OA monitoring in the OSPAR region. SGOA discussed the topics that should be covered, identifying measurement of pH and pCO_2 as an important topic that could be considered for inclusion. SGOA 2013 prepared a document outlining the scientific justification and purpose and expected outcomes of the workshop (SGOA 2013 report, Annex 5). In addition SGOA 2014 identified the need for further discussions on uncertainties of measurements and assessment as essential. Scripps Institute of Oceanography (SIO) is the only laboratory with experience in producing intercalibration and reference materials to support measurement of TA and DIC and SGOA agreed with MCWG that it was essential to involve Andrew Dickson in a proposed workshop. The workshop will be progressed during 2015. SGOA recommend that ICES MCWG ensure progress with the QA/QC workshop and develop technical annex covering sampling, sample pretreatment, sample storage and correct use of reference materials/standards and limitations of reference materials across salinity gradients.

Discrete samples collected for DIC for later analysis are preserved (poisoned) using mercuric chloride. In some countries use of mercuric chloride has been severely restricted and even acquiring it is proving problematic. These constraints seem likely to be adopted in other countries. Since no suitable alternative biocide has been identified, this presents a significant problem for the carbonate monitoring programme. Efforts are needed to identify and test suitable alternative preservation techniques to avoid the current sampling programmes being undermined.

SGOA recommends a review of preservation techniques used for storage of samples.

Currently there are no intercomparison QA schemes or QA/QC standards for biological aspects of OA work. This situation is likely to remain unchanged until specific indicators have been developed.

6.6 Role of Assessment Criteria in OA monitoring

OA is currently part of OSPAR preCEMP monitoring (OSPAR, 2014). For components of the voluntary pre-CEMP, such as OA carbonate parameters, to be adopted into the mandatory CEMP, OSPAR specifically requires that technical guidance, QA tools and assessment criteria are in place. The development of quantitative assessment criteria for ocean acidification in the OSPAR area assumes that it is possible to distinguish different levels of acidity (or associated conditions) on the basis of their acceptability and need for remedial management action. Three categories are frequently used for other marine monitoring, with objective means to distinguish them: acceptable (green, in a 'traffic lights' colour-coding); some cause for concern (orange/amber); and unacceptable (red). While such assessment criteria can apply to single measurements, it is more usual for data to be spatially and/or temporally aggregated, providing mean values for the locality and timescale of concern. OSPAR use two types of assessment criteria in the CEMP: criteria which represent a deviation from natural conditions ("background"); and criteria which demark a level representing concern, taking into account the precautionary principle. These can be applied to pressure and impact indicators. For example with respect to hazardous substances "Background Assessment Concentrations" and "Environmental Assessment Criteria" have been adopted; the latter representing ecotoxicological thresholds below which there is confidence that deleterious effects will not be observed in the marine environment (OSPAR, 2009). This is graphically represented with a variation of the traffic light system: Blue (at background); green (acceptable); red (unacceptable), enabling simple communication of assessment outputs to a non-technical audience.

For chemical pollution involving toxic compounds, there are well-established methodologies for criteria setting, mostly based on lethal or sublethal impacts on model organisms. This approach is most straightforward for synthetic contaminants, where all sources are anthropogenic; however, similar methods can be applied to naturally occurring chemicals, e.g. heavy metals or nutrients, providing that 'clean' baselines can be established, the main sources are known, and pollutant dynamics are relatively well understood. The setting of thresholds is more problematic for stressors that naturally occur over a very wide range of values that have global drivers (causing long-term trends; i.e. a changing baseline) and where biological responses are complex and uncertain. All those factors apply to ocean acidification.

Good progress has been made in developing protocols for measuring pH and other carbon chemistry parameters, with strong ICES involvement (Hydes *et al.*, 2013). However, while high data quality is a prerequisite for meaningful assessment, methods and measurements do not directly define acceptability criteria, since information is also needed on ecological consequences of different conditions. For ocean acidification the situation is complicated by:

- The multiple chemical parameters affected (pCO_2; ionic concentrations of H^+, carbonate and bicarbonate; carbonate saturation state). Components of that suite, although closely linked, do not necessarily all change together.

- The inherent variability of such carbon chemistry parameters, particularly in shelf seas and coastal waters (Provoost *et al*., 2010; Duarte *et al*., 2013). This is due to both physico-chemical and biological processes, operating on hourly to-seasonal time-scales and on metre-to-kilometre spatial scales, both vertically and horizontally.
- The variability of organisms' responses to ocean acidification (Kroeker *et al*., 2013; also see Section 7), without clear and consistent distinctions between 'safe' and 'dangerous' levels. In addition to taxonomic differences that may be at the strain level, organisms may be affected differently by different components of the chemical changes (e.g. calcifying phytoplankton increasing photosynthesis in response to higher CO_2, but decreasing calcification in response to decreased pH/carbonate). Interactions with nutritional status and other stressors are complications that provide additional challenges to single-value assessment criteria.

Nevertheless, consistent means of tracking ecologically meaningful changes are needed, and pH and carbonate saturate state are the two parameters that would seem to provide the most suitable basis for developing quantitative assessment of ocean acidification. But provisos are necessary: because of existing variability, pH values *per se* have limited usefulness for comparative purposes; instead pH change is likely to be more meaningful, either in pH units or as a ratio to existing temporal variability. The latter can be estimated at the global scale from models (Figure 14), with potential for high resolution regional projections; however, it requires extensive data collection for direct site-specific computation, and the logarithmic scaling of pH complicates the interpretation of this ratio. The inclusion of information on existing, 'baseline' pH variability within assessment criteria assumes that organisms/ecosystems currently exposed to high variability will be more tolerant of future change than those used to more stable conditions. While intuitively attractive, that concept has not been demonstrated for ocean acidification.

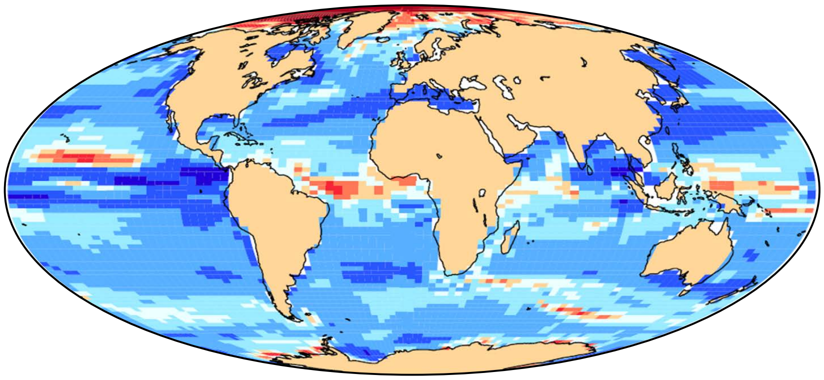

Figure 14. Potential ecosystem impact of pH change, as ratio of surface change (2100 values minus 2000 values, under scenario A1B) to current annual pH variability. ***L Gregoire and A Ridgwell/UKOA unpublished.***

The rationale for basing assessment criteria on carbonate saturation state, Ω (with values differing slightly between Ω aragonite and Ω calcite) is that calcification requires more metabolic energy when Ω is decreased, and that unprotected carbonate structures dissolve when $\Omega < 1.0$. Model-based global maps of the depth of saturation horizons (below which $\Omega < 1.0$) have been produced (Feely *et al*., 2004; Guinotte *et al*., 2006), and the shoaling of such horizons has been recorded in the Iceland Basin (Olafsson *et al*., 2009). Assessment criteria based on Ω would preferably also need to be rate-based; i.e. not just the mapped position of saturation horizons, but the rate of Ω change, that could be integrated through the total water column in shelf seas, or to a specified depth in the open ocean.

If upper ocean water chemistry were directly tracking changes in atmospheric CO_2, year-to-year change in measured pH and Ω would be near-uniform across the OSPAR region, from polar waters to the near-tropics. However, such uniformity is unlikely (and has not been observed to date). Areas of higher-than-average pH or Ω change, as identified from monitoring, are of particular interest, not only to provide the focus for more intensive biological studies, but also potentially to assist in the identification of other driving factors (that might be amenable to more direct management).

The use of a limited suite of indicator organisms as the basis for assessment criteria for ocean acidification is currently considered premature. That does not mean that monitoring potentially sensitive species (e.g. cold-water corals) should not occur, but it is not yet possible to define reliable measures of biological impacts that can be uniquely linked to ocean acidification and thereby used to define acceptability thresholds. However, there will be a role for assessment criteria for biological effects as indicators are developed.

Further discussion focused on the purpose of assessment criteria in communicating the threat of OA in the context of the requirement for mitigation or other management action. OA is a pervasive and inexorable consequence of the projected increase in atmospheric CO_2, albeit at variable rates in different regions/areas. Moreover it is essentially irreversible on practical time-scales. While identifying areas that are subject to most rapid acidification to OA is of value, it should not obscure the message that OA is progressive and a concern for all marine areas.

For climate change a global mean temperature increase of 2°C has been used as a reference point, representing the threshold above which it is considered there is a risk of dangerous anthropogenic interference[6] with the climate system; i.e. "dangerous climate change" (Copenhagen Accord, 2009; Anderson *et al*., 2011). There are no equivalent accepted reference points for ocean acidification. Such thresholds, while having foundations in science, are ultimately policy reference points in that they require a societal judgement on an accepted degree of impact to aid formulation of policy measures and target setting for mitigation and adaptation strategies.

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[6] The 2°C threshold temperature increase is not necessarily 'dangerous' *per se*, but represents a threshold where a suite of other climate-driven changes (sea level rise, extreme events, etc.) and the triggering of positive feedbacks are considered "dangerous."

6.7 References

Anderson, K., Bows, A. 2011. Beyond “dangerous” climate change: emission scenarios for a new world. Phil. Trans. R. Soc. A, 369: 20–44. http://rsta.royalsocietypublishing.org/content/369/1934/20.full.pdf+html.

Copenhagen Accord. 2009. FCCC/CP/2009/L.7. Copenhagen, Denmark: United Nations Climate Change Conference. http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf.

Duarte, C.M., Hendriks I.E., Moore T.S., Olsen Y.S., Steckbauer A., Ramajo L., Carstensen J., Trotter J.A. and McCulloch M. 2013. Is ocean acidification an open-ocean syndrome? Understanding anthropogenic impacts on seawater pH. Estuaries & Coasts, 36: 221–236.

Feely, R.A., Sabine, C.L., Lee, K., Berelson, W., Kleypas, J., Fabry, V.J. and Millero, F.J. 2004. Impact of anthropogenic CO2 on the CaCO3 system in the oceans. Science 305: 362–365.

Guinotte, J.M., Orr, J., Cairns, S., Freiwald, A., Morgan, L. and George, R. 2006. Will human-induced chemistry alter the distribution of deep-sea scleractinian corals? Frontiers Ecol. Environ. 4: 141–146.

Hydes, D. J., McGovern, E., and Walsham, P. (Eds.) 2013. Chemical aspects of ocean acidification monitoring in the ICES marine area. ICES Cooperative Research Report No. 319. 78 pp. International Council for the Exploration of the Sea. Copenhagen. http://www.ices.dk/sites/pub/Publication%20Reports/Cooperative%20Research%20Report%20(CRR)/crr319/ICRR%20NO319%20web.pdf.

IWG-OA. 2014. Strategic Plan for Federal Research and Monitoring of Ocean Acidification Interagency Working Group on Ocean Acidification. http://oceanacidification.noaa.gov/IWGOA/ResearchStrategy.aspx.

Kroeker, K.J., Kordas, R.L., Crim, R., Hendriks, I.E., Ramajo, L., Singh, G.S., Duarte, C.M., and Gattuso J.P. 2013. Impacts of ocean acidification on marine organisms: quantifying sensitivities and interaction with warming. Global Change Biology, 19: 1884–1896; doi: 10.1111/gcb.2013.19.issue-6/issuetoc.

Newton, J., Feely, R.A., Jewett, E.B., Williamson P. and Mathis M. 2014. Global Ocean Acidification Observing Network: Requirements and Governance Plan. First edition: September 2014. http://www.goa-on.org/docs/GOA-ON_Plan_final_Sept_2014.pdf.

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

OSPAR. 2009. Background Document on CEMP assessment criteria for the QSR 2010. OSPAR Monitoring and Assessment Series. Publication 461. OSPAR Commission, London http://qsr2010.ospar.org/media/assessments/p00390_supplements/p00461_Background_Doc_CEMP_Assessmt_Criteria_Haz_Subs.pdf.

OSPAR. 2014. OSPAR Coordinated Environmental Monitoring Programme (CEMP): Update 2014. (Reference number: 2010-1, amended in 2011[7], 2012, 2013, 2014) OSPAR Commission London http://www.ospar.org/documents/dbase/decrecs/agreements/10-01e_the%20cemp.doc.

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[7] Amendments in 2011 to Appendix 1, 3, 4, 8, 9, 10, 11, 12, 13, 14; 2012: addition of Appendix 16; [2013 revision updates main text, 2014-revisions to paragraphs 7, 8, 19 and Appendix 16].

Provoost, P., van Heuven, S., Soetaert, K., Laane, R.W.P.M. and Middelburg, J. J. 2010. Seasonal and long-term changes in pH in the Dutch coastal zone, Biogeosciences, 7: 3869–3878, doi:10.5194/bg-7-3869-2010.

7 ToR F: Inform the development of biological effects indicators for ocean acidification, including the identification of suitable species and key areas

7.1 Ecological indicators

The current state of understanding of how individual species respond to OA is growing and the literature continues to add new species to a list of taxa (Table 2) that are either directly or indirectly sensitive to the impacts of declining ocean pH. Our understanding of the mechanisms by which individual species are affected by OA remains an emerging area of research. Moreover, we do not have suitable biochemical or morphological metrics with which to quantify the impacts of OA on most species. It is also likely that useful metrics are likely to be species-specific. Consequently, no universal metric can be applied to all species. For example, research in the Southern Ocean (Bednaršek *et al*., 2012) has demonstrated that pteropods belonging to the species *Limacina helicina antarctica* exhibited shell erosion in response to reduced pH. The challenge is that measurements that are suitable for *L. helicina antarctica* may not be suitable for other species because thecosomate pteropods display a high degree of morphological diversity (e.g. Figure 15). The vast area of the OSPAR domain, which spans a broad latitudinal range and contains waters that range in depth from the coast to the bathypelagic, contains species potentially sensitive to OA. Identification of which of these species should be selected for monitoring and description of appropriate morphological or biochemical metrics that can be used to document OA impacts is premature. For these reasons, SGOA recommends that a broad suite of organisms likely sensitive to OA, be collected and archived during the initial OA monitoring programme. This archive will serve as a repository of specimens that can be retrospectively examined for evidence of OA responses once appropriate indicator metrics are developed.

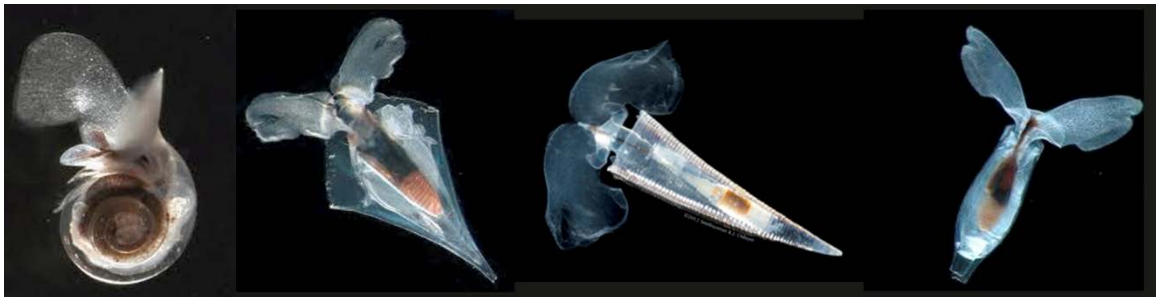

Figure 15. Examples of thecosomate pteropod morphological diversity. Image credits (left to right): R. Hopcroft, R, Hopcroft, K. Osborn, R. Hopcroft.

In the absence of sufficient data to provide guidance on specific species that are likely to be sensitive to OA, we have provided a list of taxa (Table 2) for which there are published data documenting responses to OA in either laboratory or field studies. Selection of reference specimens of appropriate indicator species from within the groups listed in Table 2 is recommended as a starting point for biological monitoring. The selection of species that are appropriate to monitoring should be undertaken by surveying existing biological inventory databases for each of the OSPAR regions. We recommend that this inventory be completed early within the initial six-year monitoring cycle of the proposed monitoring strategy.

In terms of potential indicator organisms, it is currently possible to make some general statements regarding potential suitability. The thecosomate pteropods are a planktonic group, which contains some species that have a high likelihood of being useful as OA indicators (Table 3).

Once all potentially vulnerable species have been identified in each OSPAR region, the next phase will be selection of a subset of species from each broader taxonomic category for monitoring. It is recommended that the criteria for selection of species for monitoring include the following: (1) the species have broad distribution within the each of the OSPAR regions; (2) it is abundant within the time frame anticipated for monitoring; (3) practical protocols exist for sorting individuals during, or shortly after surveys; and (4) there exist long-term methods for archiving specimens so that their calcareous structures are not degraded. Broad distributions and abundance during surveys are essential to ensure that the species remains available throughout the assessment time-series. Given that regional warming is likely to be superimposed on changes in ocean pH, selection of species that are near the boundaries of their range could lead to their disappearance from the survey area over time. Effective sorting and archiving protocols are essential so that target species can be efficiently sorted from bulk samples and preserved in a manner so that anatomical structures that can inform about OA effects are not degraded during storage.

A first attempt to further identify potential indicator species within OSPAR regions has been carried out as part of a master's student literature review commissioned by the Dutch Government (Landman, 2014). From the table of potential indicator organisms prepared by SGOA 2013, three groups were shortlisted for further examination: pteropods, coccolithophores and foraminifera, based on data availability, occurrence in OSPAR areas and potential sensitivity. The report suggests, and SGOA concurred, that the organism of most promise for monitoring in the Arctic region is the pteropod *Limacina helicina* due its distribution, its sensitivity to OA, the rapid acidification expected in the Arctic, and the work done to date on preservation and analytical techniques (Bednaršek *et al.*, 2012). The sensitivity of coccolithophores was found to be strain-specific and strains are difficult to identify without molecular techniques. The report showed insufficient evidence of sensitivity of certain foraminifera species to projected OA to be recommended as indicator species at this stage. Therefore, SGOA recommends development of protocols for the collection and preservation of thecosomate pteropod shells for future evaluation of OA-driven changes in morphological characteristics.

Additional potentially useful monitoring tools included the use of settlement or dissolution plates that could be placed in potentially sensitive and control areas to monitor recruitment, growth, and erosion.

Cold-water corals such as *Lophelia pertusa* are species of high conservation concern and identification of areas where they are currently abundant is important. NOAA have recently produced a series of habitat suitability index models predicting where cold-water corals such as *Lophelia pertusa* and others would likely occur along the US Atlantic and Gulf Coasts. An example map was shown and discussed at SGOA 2014 with respect to the potential implementation of these models within the OSPAR region as a means of identifying areas where corals might have a higher probability of occurrence.

Marine Strategy Framework Directive: EU member states are also in the process of defining monitoring programmes under Article 11 of the Marine Strategy Framework Directive (MSFD Directive 2008/56/EC). While OA is not specifically considered in the eleven descriptors of Good Environmental Status, monitoring of biological parameters is required under a number of these descriptors, such as descriptor 1 on biodiversity, descriptor 4 on foodwebs and descriptor 5 on Eutrophication. There are potential synergies with this monitoring which should be explored. SGOA also highlight potential links to the European Network of Marine Research institutes and Stations (http://www.marsnetwork.org/index.php).

Table 2. Potential indicator organisms for OA responses, requiring further expert consideration. This list represents initial thoughts; it is not exhaustive, and very different recommendations for indicator species may subsequently be developed.

Group	Species	Quantitative basis for use as indicator?	Issues/Comments
Benthic			
Cold-water corals	*Lophelia pertusa*, *Madrepora* spp., *Solenosmilla* spp., *Eunicella* spp.	Slowed growth/mortality at lower depth limit, in response to raising of saturation horizon.	Mortalities may be difficult to determine without high resolution repeat ROV/AUV mapping of specific study sites. Development of morphological indices based on skeletal metrics would be necessary to document erosion/reduced or altered deposition.
Echinoderms (particularly some brittlestar species)	Some brittlestar species e.g. *Ophiothrix fragilis*	Reduced abundance (taking account of other factors) and lowered larval calcification.	*O. fragilis* particularly sensitive to OA under experimental conditions 100% larval mortality in response to pH decrease of 0.2.
Coralline Macroalgae	*Lithothamnion gracile* *L. corallioides*, *Phymatolithon calcareum*, *Lithophyllum dentatum*	Growth rate (using annual rings and changes in boron isotope composition)	Morphological techniques being developed; sensitivity to OA uncertain.
Non-Coralline Macroalgae		Increased productivity.	
Molluscs	*Littorina littorea*	Currently monitored in Dutch waters as part of OSPAR eutrophication monitoring.	Lab studies indicated reduced calcification under elevated pCO_2.
	Mytilus spp.	Currently monitored as part of contaminant assessment.	Reduced shell and byssus strength when grown under experimental treatments with elevated pCO_2 though some wild populations appear healthy undere reduced ph/high-food condition.
Calcareous Annelids (*Serpulids*)	*Serpula*	Changes tube composition (calcite/aragonite ratio, Mg/Ca ratio) in undersaturated water.	Requires special techniques.
Calcareous epiphytes and epibionts on seagrasses		i) Coverage on seagrasses (abundance) ii) $CaCO_3$ weight	Sensitive to CO_2, but restricted to areas with seagrass.
Seagrasses		Increased abundance, but unlikely to be unambiguously linked to OA	Might benefit from increased CO_2, but this response depends on other environmental conditions

GROUP	SPECIES	QUANTITATIVE BASIS FOR USE AS INDICATOR?	ISSUES/COMMENTS
Crustaceans	*Lobster (Homarus gammarus),* Crabs (*Hyas araneus*, *Cancer pagurus*)	Carapace deformities. Reduced thermal tolerance and scope for activity.	Carapace deformation in larval and juvenile lobsters exposed to elevated pCO_2 at different temperatures
Water column			
Pteropods (planktonic sea snails)	*Limacina* spp and other shelled pteropods	Abundance (taking account of other factors) Shell thickness/condition	High sensitivity to OA under experimental conditions; shell dissolution of *Limacina helicina antarctica* observed in response to existing pH variability of Southern Ocean.
Coccolithophores	*Emiliana huxleyii* and other species.	Abundance and biodiversity (taking account of other factors) Calcification Coccolith morphology/mass/malformation	Unsuitable. Coccolithophore calcification and photosynthesis response to ocean acidification is diverse, species- and even strain- specific. *Emiliania huxleyi* is probably unsuitable as an indicator; the genome variability within this species complex seems to underpin its capacity to thrive under a wide variety of environmental conditions. However, negative effects for *E. huxleyi* population, become evident at elevated CO2 levels projected for this century. Suitability of other species warrants further study. Recent studies highlighted the importance of seawater carbonate chemistry, especially CO_3^{2-}, in unraveling the distribution of heterococcolithophores, the most abundant coccolithophore life phase. A first study based in CO_2 vents showed a decrease in biodiversity in elevated CO_2 conditions.
Foraminifera	Variety of pelagic taxa (also benthic taxa)	Shell morphology/thickness	Relevant features that might be suitable for quantitative assessment currently under investigation. Long time-series potential given their presence in both historical and palaeo observations.
Bivalve larvae	Commercially cultivated species	Larval survival Calcification [both for mariculture conditions]	Risk of OA impacts on cultivated shellfish lower in Europe than in NW USA (the latter subject to strong upwelling of lower pH water) but routine chemical and biological monitoring of aquaculture facilities would nevertheless be desirable.
Phytoplankton	Range of species	Increased productivity. Abundance changes unlikely to be unambiguously linked to OA, but change in C:N ratio may be detectable	Unsuitable. Resolving impacts due to OA will be extremely difficult given their response to other hydrological, biological, and chemical factors. Rapid capacity to modify ambient chemical conditions.

Table 3. Effects of OA on pteropods. Experimental studies reported in the literature (from Landman, 2014).

SPECIES	CO_2 SYSTEM PARAMETERS EXAMINED	STUDY DURATION	EFFECT	FIRST MEASURED EFFECT	COMMENTS	REFERENCE
Cavolinia inflexa	pH: 8.1; 7.82; 7.51 pCO_2: 380; 857; 1713 µatm [1] Ω_a: 2.9; 1.66; 0.86 [2]	13 d	Decreased shell length with increased pCO_2. Shell almost absent at lowest pH.	Only trend determined.	Larvae	Comeau *et al.* (2010a)
Clio pyramidata	Ω_a:<1	48 h	Aragonite undersaturation and shell dissolution.	Only trend determined.	No exact numbers or other parameters available.	Orr (2005)
Limacina helicina antarctica	pH: 8.071; 7.810; 7.650 pCO_2: 372; 664; 994 µatm Ω_a: 1.50; 0.86; 0.61	24 h	Reduced respiration with increased pCO_2.	Only trend determined.		Seibel *et al.* (2012)
Limacina retroversa	pH: 8.2; 8.0; 7.8; 7.6 pCO_2: 280; 350; 750; 1000 µatm	8 d	Reduced survival and shell growth. Increased shell dissolution below pH 7.8.	pH 7.8	In combination with decreasing salinity (from 80 % in situ levels) decreased survival from pH 7.8, additional decrease in shell growth from pH 7.8	Manno *et al.* (2012)
Limacina retroversa	pCO_2: 350; 880 µatm	7 d	Reduced survival and increased shell degradation.	pCO2: 880 µatm	No synergistic effect with temperature.	Lischka and Riebesell (2012)
Limacina helicina	pCO_2: 350; 650; 880 µatm	7 d	Reduced mobility and increased shell degradation.	pH 7.78	Synergistic effect with temperature.	Lischka and Riebesell (2012)
Limacina helicina	pH: 8.09; 7.78 pCO_2: 350; 765 µatm Ω_a: 1.9; 1.0	6 h	Reduced calcification	pH 8.04		Comeau *et al.* (2009)

SPECIES	CO_2 SYSTEM PARAMETERS EXAMINED	STUDY DURATION	EFFECT	FIRST MEASURED EFFECT	COMMENTS	REFERENCE
Limacina helicina	pH: 8.19; 8.04; 7.91; 7.77; 7.62 pCO_2: 280; 380; 550; 760; 1120 µatm	8 h	Reduced calcification		At increased temperature (4°C), the decrease in calcification rate was smaller. Undersaturated for aragonite in highest pCO_2 conditions.	Comeau *et al.* (2010b)

7.2 References

Bednaršek, N., Tarling, G. A., Bakker, D. C., Fielding, S., Cohen, A., Kuzirian, A., McCorkle, D., *et al.* 2012. Description and quantification of pteropod shell dissolution: a sensitive bioindicator of ocean acidification. Global Change Biology, 18: 2378–2388.

Comeau, S., Gorsky, G., Jeffree, R., Teyssié, J.-L., and Gattuso, J.-P. 2009. Impact of ocean acidification on a key Arctic pelagic mollusc (*Limacina helicina*). Biogeosciences, **6**: 1877–1882.

Comeau, S., Gorsky, G., Alliouane, S., and Gattuso, J.-P. 2010a. Larvae of the pteropod *Cavolinia inflexa* exposed to aragonite undersaturation are viable but shell-less. Marine Biology, 157: 2341–2345.

Comeau, S., Teyssié, J.L., and Gattuso, J.-P. 2010b. Response of the Arctic pteropod *Limacina helicina* to projected future environmental conditions. PLoS ONE, 5: e11362. doi:10.1371/journal.pone.0011362.

Landman, T.W. 2014. Finding an indicator species for ocean acidification in the OSPAR area. Master thesis, Radboud Univeristy Nijmegen.

Lischka, S. and Riebesell, U. 2012. Synergistic effects of ocean acidification and warming on overwintering pteropods in the Arctic. Global Change Biology, 18: 3517–3528.

Manno, C., Morata, N., and Primicerio, R. 2012. *Limacina retroversa*'s response to combined effects of ocean acidification and sea water freshening. Estuarine, Coastal and Shelf Science, 113: 163–171.

Orr, J.C. Fabry, V.J., Aumont, O., Bopp, L. Doney, S.C., Feely, R.A., Gnanadesikan, A., Gruber, N., Ishida, A., Joos, F., Key, R.M., Lindsay, K., Maier-Reimer, E., Matear, R., Monfray, P., Mouchet, A., Najjar, R.G., Plattner, G.-K., Rodgers, K.B., Sabine, C.L., Sarmiento, J.L., Schlitzer, R., Slater, R.D., Totterdell, I.J., Weirig, M.-F. Yamanaka, Y., and Yool, A. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. Nature 437:681–686.

Seibel, B.A., Maas, A.E., and Dierssen, H.L. 2012. Energetic plasticity underlies a variable response to ocean acidification in the pteropod, *Limacina helicina antarctica*. PLoS ONE 7: e30464. doi:10.1371/journal.pone.0030464.

8 ToR G: Elaborate reporting requirements to ICES (taking account of the information in table at OSPAR MIME 2011 SR Annex 6)

8.1 Ocean acidification and carbonate system data; Background

The ICES DataCentre (ICES-DC) is the repository for OSPAR CEMP data and Contracting Parties are required by OSPAR to submit monitoring data to ICES. SGOA was tasked with defining the reporting requirements for OSPAR OA monitoring.

OA-relevant chemical and biological data are also reported to a variety of other international data centres, often as a requirement of specific projects. Examples are the Carbon Dioxide Information Analysis Centre (CDIAC) and PANGAEA (see SGOA 2012 report, Annex 6). Global ocean carbon data synthesis products such as the Surface Ocean CO_2 Atlas (SOCAT) and Global Ocean Data Analysis Project (GLODAP) are also available and these include additional levels (secondary) of quality control. SGOA recognized that OSPAR OA-monitoring may be linked to other monitoring/research activities which may define the preferred reporting route for these data.

Given the recommendation for OSPAR monitoring to be compatible with other regional and global monitoring OA monitoring activities SGOA considered that, as well as developing protocols for reporting CEMP OA data to ICES, it was also necessary to consider how ICES-DC would interface with other international OA data centres to maximise data exchange and availability and limit requirements for multiple reporting of datasets to different data centres. Assessment of OA and its impacts would ultimately require observations of physical, chemical and biological parameters. SGOA, working closely with the ICES MCWG, addressed this by inviting a number of OA data experts associated with different data centres/products to participate in data discussion sessions. These included ICES-DataCentre (Hans Mose Jensen, Marilynn Sørensen), CDIAC (Alex Kozyr, US), GLODAPV2 (Toste Tanhua, DE; Are Olsen, NO), SOCAT (Benjamin Pfeil, NO), NOAA OA Data Stewardship (Liqing Jiang, US). These are described in the following sections.

8.2 Development of ICES OA data reporting formats: Current Status

The ICES-DataCentre (ICES-DC) is the primary repository of marine monitoring data for OSPAR and OSPAR rules require that Contracting Parties, (CPs), report their CEMP data to ICES. ICES explained that ocean acidification parameters could be reported to ICES environment database (ERF 3.2 format) or oceanographic database (IOF free format using BODC codes). At present the ICES oceanographic system does not include method information for the standard parameters, but if reported using new BODC codes then this allows for some method information to be included. The ERF 3.2 format used in the ICES environment database uses the ICES vocab parameter list and accepts metadata including detailed method and QA information. An analysis of carbonate system data in the databases in 2012 showed a substantial pH dataset but with little associated QA information and mostly relating to electrode determinations.

SGOA and MCWG together elaborated basic parameters, metadata and checks for the ocean acidification parameters pH, total alkalinity, dissolved inorganic carbon and partial pressure of carbon dioxide. In defining these SGOA/MCWG considered compatibility with reporting requirements for CDIAC. These recommendations have been implemented for the ICES environment database which stores metadata directly with the data (ERF 3.2 Format). Ireland and UK test data submissions have been used to check the quality control of the database so the OSPAR/ICES discrete (bottle) database is now operational for reporting carbonate parameters. All data requirements can be viewed in the DataCentre Data Request form for Ocean Acidification data. Data submissions are now required to test whether data submitted to ICES will pass the quality control requirements of CDIAC. The ICES Environment database also has flexibility to accept biological effects data.

The environment database is best suited for reporting discrete (bottle) data. The oceanographic format is more suitable for (semi-)continuous data, such as from pCO_2 sensors. Entering ocean acidification parameters into the ICES oceanographic database is possible without metadata. Whether these data would meet the reporting requirements of other international ocean carbon data centres such as CDIAC requires further investigation but at present SGOA do not recommend reporting OSPAR OA data to the Oceanographic database.

8.3 Other Global carbon/OA data activities

8.3.1 NOAA Ocean Acidification Scientific Data Stewardship (OADS)

Liqing Jiang from the US National Oceanographic Data Center (NODC) presented the National Oceanic and Atmospheric Administration (NOAA)'s OA data management activities at SGOA 2014. Established in 2012, the Ocean Acidification Scientific Data Stewardship (OADS) Project's near term goal is to manage datasets that are generated from NOAA Ocean Acidification Program funded projects. Liqing demonstrated the main components of the OADS data management (Figure 16). This includes a new OA metadata template that can document various types of OA dataset (including physiological response OA datasets), an envisioned OA data submission interface, and a newly launched data search portal. Liqing also talked about the exchange of ocean carbon data with the Carbon Dioxide Information Analyses Center (CDIAC). The long-term vision of the Project is to build a US national OA data exchange service, with the goal of providing dedicated OA data discovery and access to both modern and historical OA datasets that are collected worldwide. A key issue identified in discussions at SGOA was the need to establish a mechanism to prevent data duplications in data management. For example, one way of doing this is through matching the platform (e.g. research vessel) ID and the temporal coverage, or the EXPOCODE.

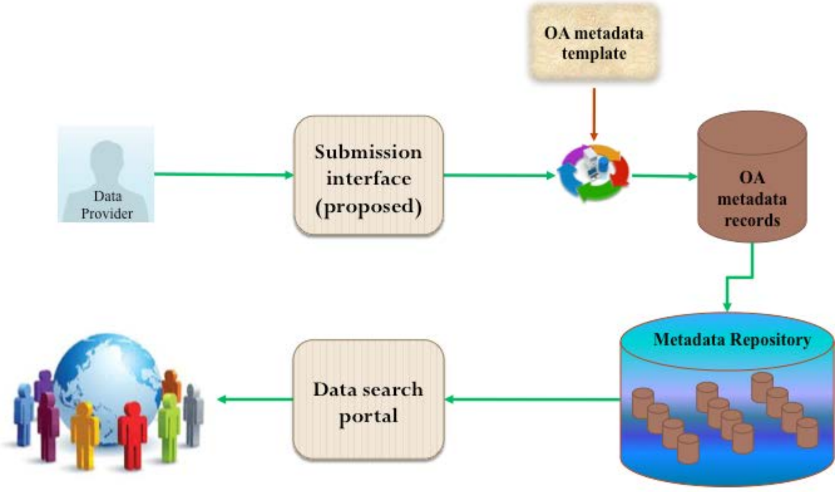

Figure 16. Main components of NOAA’s ocean acidification data management.

Liqing Jiang (US) SGOA 2014

8.3.2 CDIAC Data Centre

Alex Kozyr of the Carbon Dioxide Information Analysis Centre (CDIAC) gave a short overview of CDIAC activities (http://cdiac.ornl.gov/). CDIAC is located at US Department of Energy’s Oak Ridge National Laboratory (ORNL) and includes the World Data Center for Atmospheric Trace Gases. CDIAC's data holdings include estimates of carbon dioxide emissions from fossil-fuel consumption and land-use changes; records of atmospheric concentrations of carbon dioxide and other radioactively active trace gases; carbon cycle and terrestrial and ocean carbon management datasets and analyses; and global/regional climate data and time-series.

CDIAC serves as a global Ocean Carbon Data repository for discrete (bottle), time-series and moorings, coastal, and surface (underway) CO_2 data (http://cdiac.ornl.gov/oceans/). The formats for reporting ocean carbon data to CDIAC are well established and available at http://cdiac.ornl.gov/oceans/submit.html. Accepted datasets are issued with a digital object identifier (DOI). CDIAC works closely with CLIVAR (Climate and Ocean: Variability, Predictability and Change; www.clivar.org) and Carbon Hydrographic Data Office (CCHDO) and NOAA NODC. CDIAC quality controls carbon hydrography datasets, merges them with latest hydrographic data files, posts them on the CDIAC web, and sends the merged set to CCHDO and NOAA NODC. A process has been put in place for automated synchronised transfer of Ocean CO_2 data to the NODC via the Mercury system. Figure 17 provides a view of CDIAC’s role in Ocean CO_2 data exchange in the OA Network. CDIAC also provides a portal to synthesis data products such as GLODAP and SOCAT (see Section 8.3.3). CDIAC confirmed that OSPAR monitoring data submitted could be flagged as OSPAR data if required.

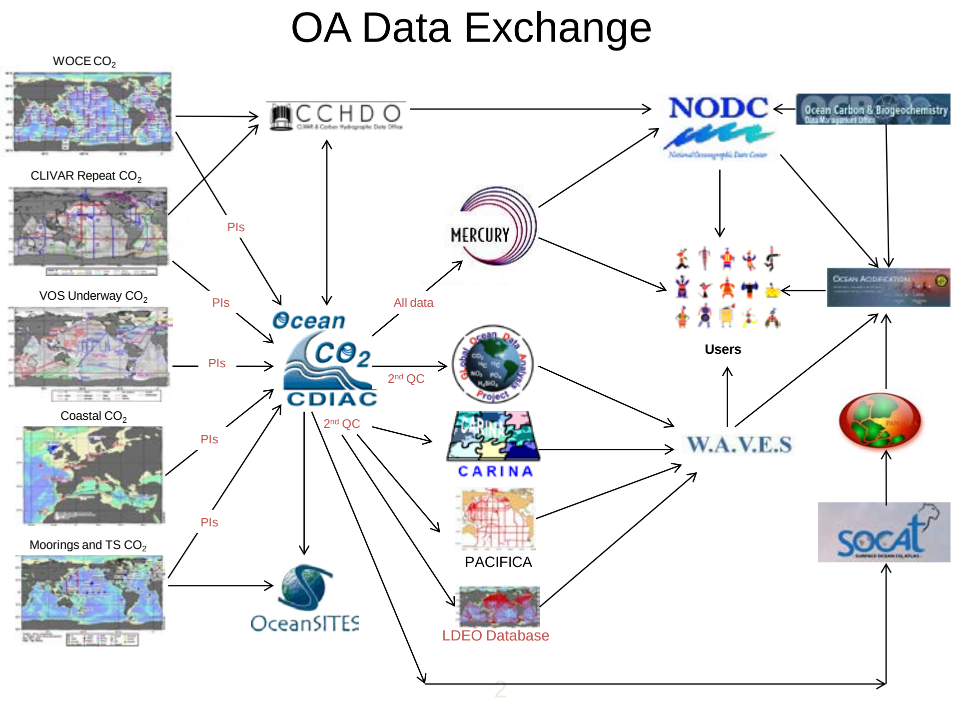

Figure 17. CDIAC role in data exchange of Ocean CO_2 data and OA network.

Alex Kozyr (US) SGOA 2013, 2014.

8.3.3 Ocean Carbon Data Synthesis Products: GLODAP and SOCAT

This text is modified from the text in (Tanhua *et al.*, 2013).

The most important aspects of the interior ocean carbon data products are that they consist of carefully quality controlled, internally consistent, data available in a common format. The Global Ocean Data Analysis Project (GLODAP) provided a dataset from the global CO_2 survey of 1990s (Key *et al.*, 2004; Sabine *et al.*, 2005), including significant historic cruises. A second data collection for the Arctic, Atlantic and Southern Oceans was published in 2009; CARINA (Carbon IN the Atlantic) (Key *et al.*, 2010 and additional articles in the special issue). Recently a data product covering the Pacific Ocean including data from 213 cruises (additionally 59 datasets from line P, and 34 WOCE cruises) was published; PACIFCA (PACIFic ocean Interior CArbon) (Suzuki *et al.*, 2013). In addition, a current effort known as GLODAPv2, due for release in early 2015, aims to merge those three products and add additional data not included in any of those. These data products consist of two or three main products; individual cruise files, merged data products and (for GLODAP) gridded products (Key *et al.*, 2004). The individual cruise files are all reported in a common format with standardized units and quality flags, and were in all instances scrutinized and quality controlled (1st level of QC). The primary QC is designed to find outliers, but is insensitive to systematic biases; those can be assessed by the so-called secondary quality control (2nd QC). Biases in the reported data are often due to incorrectly quantified standard concentrations, blank problems or other analytical difficulties that are very difficult to assess in the field. Note that 2nd QC only addresses the accuracy of the data, not the precision.

The gridded products are valuable components of the data products, particularly for easy comparison with model results and for calculating inventories of properties such as anthropogenic carbon (C_{ant}). Due to sparseness on the data, significant interpolation and extrapolation errors can be expected on local scales (e.g. Schneider *et al.*, 2012).

Surface ocean pCO_2 data products are also available from two different but complementary sources: The LDEO pCO_2 data product (V2013) contains 9 million surface pCO_2 data points measured between 1957 and 2013 (Takahashi *et al.*, 2013) from which climatological fields have been constructed (Takahashi *et al.*, 2009); The SOCAT data product contains more than 10 million datapoints over the period 1968–2011 (Bakker *et al.*, 2013; Pfeil *et al.*, 2013). SOCAT is available as a merged product, individual cruise files (in a common format) and also as a gridded product (Sabine *et al.*, 2013).

The access to these products can be found here:

GLODAP	http://cdiac.ornl.gov/oceans/glodap/
CARINA	http://cdiac.ornl.gov/oceans/CARINA/
PACIFICA	http://cdiac.ornl.gov/oceans/PACIFICA/
GLODAPv2	http://cdiac.ornl.gov/oceans (will be published in 2015)
LDEO pCO_2	http://cdiac.ornl.gov/oceans/LDEO_Underway_Database/
SOCAT	http://www.socat.info/

Are Olsen (NO) SGOA 2012; Toste Tanhua (DE) SGOA 2013, 2014; Benjamin Pfeil (NO) SGOA 2013

8.4 Ocean acidification and carbonate system data. Key challenges for managing OSPAR data

SGOA considered issues and protocols for reporting (pre-)CEMP OA data to ICES as the regional data centre for OSPAR and HELCOM. However, the ocean carbon monitoring community currently submits data to other international data centres rather than ICES. These carbon data are then available for incorporation in various regional and global data synthesis products as outlined above. It is essential that OSPAR OA monitoring data also contribute to the global observing network. OSPAR OA data handling protocols should be developed with a view to enhancing global efforts. This requires that data centres, including ICES, should maximise data exchange and availability and where possible avoid requirements for multiple reporting by data originators of datasets to different data centres. Moreover, ecosystem assessment (including OA) will increasingly require collecting integrated physical, chemical and biological data and new technology will increasingly add high volume datasets. This will present many challenges for data handling.

In summary SGOA noted that:

- The ICES DataCentre (ICES-DC) is the repository for OSPAR CEMP data and Contracting Parties are required by OSPAR to submit monitoring data to ICES.
- There are two ICES databases that can accept carbonate-system data. The ICES environmental database is a relational database requiring reporting in ERF 3.2 format. It can accept detailed metadata/QC information but though well suited for discrete sample data it is not well suited for high

volume semi-continuous data (e.g. from pCO_2 sensors). The ICES ERF 3.2 database is also able to accept biological effects data.

- The oceanographic database allows for free format reporting but is very limited in its ability to accept associated metadata and QC information. OA-relevant chemical and biological data are also reported to a number of other international data centres, often as a requirement of specific projects. An example is the Carbon Dioxide Information Analysis Centre (CDIAC) which is a key international data repository for ocean carbon data. Moreover, the US Ocean Acidification Scientific Data Stewardship initiative provides a template that is likely to be standard for global OA monitoring.
- Global ocean carbon data synthesis products such as the surface pCO_2 atlas (SOCAT) and GLODAP(V2) are also available and these include additional levels of quality control.
- SGOA recognized that OA-monitoring may be linked to other monitoring/research activities, for example by adding OA chemistry parameters to monitoring ostensibly for other purposes, such as fisheries or hydrographic surveys. This which may define the preferred reporting route for these data. Moreover, reporting requirements should enable OA parameters to be retained with the full dataset.
- As an important step to initiate contact between relevant data managers, SGOA provided a forum for interaction between various data experts, specifically ICES-DC with CDIAC, NOAA NODC and key scientists engaged in SOCAT and GLODAP.

The potential for data exchange between key data centres ICES and CDIAC was discussed by SGOA. It is not clear if the CDIAC reporting formats and QC protocols are transferable to ICES and this needs to be investigated. The ICES DataCentre will communicate directly with CDIAC to compare reporting formats and see how useful their model/tools are for ICES. The CDIAC metadata forms for discrete and underway pCO_2 measurements are available at http://mercury-ops2.ornl.gov/OceanOME/.

The ultimate goal should be to make data submission as simple as possible and also to make the reporting as flexible as possible since measurement platforms, methods, etc. will evolve over time. It is thus positive that it is fairly easy for the ICES-DC to add new parameters to the database. There is a clear need for more discussions of how effects of OA can be reported and the development of this reporting needs to follow the evolution of biological indicators.

This ideal scenario would require data centres to have common data exchange protocols in place. It was noted that CDIAC already have an automated data transfer to NODC for OA data which may provide a model.

8.5 Data reporting recommendations

- OSPAR OA monitoring data and associated QC and metadata should be reported to the ICES *Environmental database* using formats as stipulated by SGOA and MCWG (ERF 3.2 format for discrete sample data). However, this database is not well suited to collect continuous sensor data e.g. pCO_2. The alternative ICES *Oceanographic database* is at present unsuited to the collection of OSPAR OA monitoring data due to limitations in storing relevant QC/method metadata.
- OSPAR Contracting Parties should report relevant riverine input data to the OSPAR RID database.
- It is not recommended that calculated carbonate parameters are reported. Should they be so, they should be clearly flagged and all constants applied in the derivation of calculated parameters documented and reported.
- It is further recommended that OSPAR ocean carbon and metadata are reported to the CDIAC international database, according to the internationally standardised formats. OSPAR data in CDIAC should be flagged as such. ICES should explore the potential for automated data exchange with CDIAC when suitable data are available. Common data exchange formats for OA monitoring data are required.
- OSPAR data should be collected and reported so as to be available to the global science community and suitable for inclusion in key OA-relevant global data-synthesis products, specifically SOCAT (surface pCO_2 atlas) and GLODAP. Given the additional quality control and corrections applied to these data products these may also prove useful for developing OSPAR assessment products, recognizing that GLODAP primarily covers discrete sample surface and subsurface carbonate data for oceanic waters and that SOCAT only holds continuous surface pCO_2 data.
- Given the inevitability for replication of data in different data centres it is critical that traceability is improved, for example through the use of Universally Unique Identifiers (UUIDs) such as Digital Object Identifiers (DOI).

8.6 References

Bakker, D. C. E., Pfeil, B., Smith, K., Hankin, S., Olsen, A., Alin, S.R., Watson, A.J. 2013. An update to the Surface Ocean CO_2 Atlas (SOCAT version 2). *Earth System Science Data Discussions*, 6: 465–512, doi: 10.5194/essdd-6-465-2013.

Key, R. M., Kozyr, A., Sabine, C. L., Lee, K., Wanninkhof, R., Bullister, J. L., Peng, T. H. 2004. A global ocean carbon climatology: Results from Global Data Analysis Project (GLODAP), Global Biogeochem Cycle, 18: GB4031, doi:1029/2004GB002247.

Key, R. M., Tanhua, T., Olsen, A., Hoppema, M., Jutterström, S., Schirnick, C., Mintrop, L. 2010. The CARINA data synthesis project: introduction and overview, Earth Syst. Sci. Data, 2: 105–121, doi:10.5194/essd-2-105-2010.

Pfeil, B., Olsen, A., Bakker, D.C.E., Hankin, S., Koyuk, H., Kozyr, A. and Yoshikawa-Inoue, H. 2013. A uniform, quality controlled Surface Ocean CO_2 Atlas (SOCAT), Earth Syst. Sci. Data, 5: 125–143, 10.5194/essd-5-125-2013.

Sabine, C. L., Key, R. M., Kozyr, A., Feely, R. A., Wanninkhof, R., Millero, F. and Lee, K. 2005. Global Ocean data analysis project (GLODAP): Results and data, ORNL/CDIAC, Oak Ridge, Tennessee, USA, NDP-083.

Sabine, C. L., Hankin, S., Koyuk, H., Bakker, D. C. E., Pfeil, B., Olsen, A. and Yoshikawa-Inoue, H. 2013. Surface Ocean CO_2 Atlas (SOCAT) gridded data products, Earth Syst. Sci. Data, 5: 145–153, 10.5194/essd-5-145-2013.

Schneider, A., Tanhua, T., Körtzinger, A., and Wallace, D. W. R. 2012. An evaluation of tracer fields and anthropogenic carbon in the equatorial and the tropical North Atlantic, Deep Sea Research Part I: Oceanographic Research Papers, 67: 85–97, 10.1016/j.dsr.2012.05.007.

Suzuki, T., Ishii, M., Aoyama, M., Christian, J. R., Enyo, K., Kawano, T. and Sabine, C. 2013 PACIFICA Data Synthesis Project, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, US Department of Energy, Oak Ridge, Tennessee.

Takahashi, T., Sutherland, S. C., and Kozyr, A. 2013. Global Ocean Surface Water Partial Pressure of CO_2 Database: Measurements Performed During 1957–2012 (Version 2012).

Takahashi, T., Sutherland, S. C., Wanninkhof, R., Sweeney, C., Feely, R. A., Chipman, D. W. and de Baar, H. J. W. 2009. Climatological mean and decadal change in surface ocean pCO_2, and net sea-air CO2 flux over the global oceans (56: 554, 2009), Deep-Sea Res. I, 56: 2075–2076, doi:10.1016/j.dsr2.2008.12.009.

Tanhua, T., Bates, N. R., and Körtzinger, A. 2013. The marine carbon cycle and ocean carbon inventories, in: Ocean Circulation and Climate, 2nd Ed. A 21st century perspective, edited by: Siedler, G., Griffies, S., Gould, J., and Church, J., Academic Press.

9 ToR H: Report a first assessment of all available data in the OSPAR maritime area

With respect to the above Term of Reference, SGOA 2012 proposed that the required assessment could focus on acidification status of scleractinian cold-water corals areas as vulnerable habitats. This was considered a more achievable task given the resources available to SGOA and the proposal was accepted by OSPAR CoG 2013. SGOA 2014 also carried out an assessment of available published information on long-term OA trends for the OSPAR Regions.

9.1 Ocean Acidification: an assessment of current and projected exposure of cold-water coral areas in the Northeast Atlantic

A SGOA subgroup, with contributions from additional cold-water coral, physical oceanography and modelling experts, carried out this task. The assessment is available at Annex 6. The cornerstone of this work was modelled current status and end of century projections for the seabed aragonite saturation state using two different approaches. This was carried out by Are Olsen and Jerry Tjiputra (NO, UIB). The assessment also provides the ecological and hydrographic context. The assessment was prepared by Are Olsen (NO), Jerry Tjiputra (NO), Evin McGovern (IE), Jason Hall-Spencer (UK), Melissa Chierici (NO), Martin White (IE), Johanna Järnegren (NO), Murray Roberts (UK).

9.2 Long-term trends in Ocean Acidification in the OSPAR area

A separate SGOA subgroup with additional expert input collated published information on long-term temporal trends for OA in the OSPAR Regions (Annex 7). It is difficult to compare acidification rates reported, considering the different approaches, such as parameters, target areas, scales, timing and frequency of sampling. Nonetheless, acidification of surface waters and, to a lesser extent due to the lag time in penetration of anthropogenic carbon, deeper water of the Northeast Atlantic over recent decades is evident. The contributors to this report were Triona McGrath (IE), Caroline Kivimae (UK), Solveig Olafsdottir (IC), Evin McGovern (IE), Toste Tanhua (DE), Richard Feely (US) and Are Olsen (NO).

Annex 1: List of participants at SGOA meetings 2012–2014

NAME	COUNTRY	INSTITUTION	MEETING ATTENDED [8] (W=JOINED VIA WEBEX)
Mark Benfield Chair	United States	Louisiana State University	2014, 2013, 2012
Melissa Chierici	Norway	Institute of Marine Research	2014W, 2013, 2012
Kris Cooreman	Belgium	Institute for Agricultural and Fisheries Research (ILVO)	2014
Richard A. Feely	United States	National Oceanic and Atmospheric Administration NOAA	2014W
Claus Hagebro	Denmark	ICES	2012
Jason M. Hall-Spencer	United Kingdom	University of Plymouth	2014W, 2013
David J. Hydes	United Kingdom	National Oceanography Centre	2012
Sofia Hjalmarsson	Sweden	Swedish Agency for Marine and Water Management	2013
Hans Mose Jensen	Denmark	ICES	2013, 2012
Liqing Jiang	United States	NOAA	2014
Caroline Kivimae	United Kingdom	National Oceanography Centre	2014, 2013
Anna de Kluijver	Netherlands	Deltares	2014, 2013
Alex Kozyr	United States	Oak Ridge National Laboratory	2014W, 2013W
Evin McGovern Chair	Ireland	Marine Institute	2014, 2013, 2012
Jan René Larsen	Norway	Arctic Monitoring and Assessment Programme	2013, 2012
Shannon Meseck	United States	National Oceanic and Atmospheric Administration	2014W, 2012W
Maria Chun Nielsdóttir	Faroe Islands	Faroe Marine Research Institute	2014
Sólveig Ólafsdóttir	Iceland	Marine Research Institute	2014, 2013, 2012
Are Christian Sviggum Olsen	Norway	University of Bergen	2014, 2012
Hjalte Parner	Denmark	ICES	hjalte@ices.dk
David Pearce	United Kingdom	Centre for Environment, Fisheries and Aquaculture Science (Cefas)	2014, 2013, 2012
Benjamin Pfeil	Norway	University of Bergen	2013W

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[8] Whole or part meeting attended.

NAME	COUNTRY	INSTITUTION	MEETING ATTENDED [8] (W=JOINED VIA WEBEX)
Beth Phelan	United States	National Oceanic and Atmospheric Administration	2014W, 2012W
Hans-Otto Pörtner	Germany	Alfred-Wegener-Institute Foundation for Polar and Marine Research	2014
Murray Roberts	United Kingdom	Heriot Watt University	2013
Marilynn Sørensen	Denmark	International Council for the Exploration of the Sea	2014, 2013, 2012
Toste Tanhua	Germany	Leibniz-Institut für Meereswissenschaften	2014W, 2013W
Katrin Vorkamp	Denmark	Aarhus University	2014, 2013, 2012
Pamela Walsham	United Kingdom	Marine Scotland Science	2014, 2013, 2012
Sieglinde Weigelt-Krenz	Germany	Bundesamt für Seeschiffahrt und Hydrographie	2013, 2012
Phil Williamson	United Kingdom	University of East Anglia	2014, 2013, 2012
Anna Willstrand Wranne	Sweden	Swedish Meteorological and Hydrological Institute	2014
Patrizia Ziveri	Spain	ICREA-ICTA, Universitat Autonòma de Barcelona	2013W, 2012

SGOA also acknowledges the key contributions of the following experts to products in the final report: Alberto Borges (BE); Johanna Järnegren (NO); Marta Nogueira (P); Jerry Tjiputra (NO), Triona McGrath (IE); Martin White (IE).

Annex 2: SGOA Terms of Reference

The **Joint OSPAR/ICES Study Group on Ocean Acidification** (SGOA), chaired by Evin McGovern, Ireland, and Mark Benfield, USA, were provided the following Terms of Reference by OSPAR and adopted as a resolution at the ICES 2012 Annual Science Congress and Statutory Meeting.

a) Collate chemical data and information on ocean acidification in the OSPAR Maritime Area;

b) Seek information from relevant international initiatives on Ocean acidification; as listed in OSPAR MIME 11/3/3 (e.g. EU, Arctic Council);

c) Finalize guidelines for measuring carbonate system[9];

d) Collect and exchange information on biological effects on plankton, and macrozoobenthos;

e) Consider the strategy that would be required for an assessment framework appropriate to long-term assessment of the intensity/severity of the effects of ocean acidification, including any assessment criteria required;

f) Inform the development of biological effects indicators for ocean acidification, including the identification of suitable species and key areas[10];

g) Elaborate reporting requirements to ICES (taking account of the information in Table at OSPAR MIME 2011 SR Annex 6);

h) Report a first assessment of all available data in the OSPAR maritime area.

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[9] OSPAR Footnote to ToR c) Building on the draft guidelines coming forwards from ICES Marine Chemistry Working Group (MCWG).

[10] OSPAR Footnote to ToR f) OSPAR BDC, in understanding the interactions between ocean acidification and biodiversity agreed that although it is not possible to identify parameters at this time, there is a need for the monitoring of biodiversity aspects for MSFD to look at the issues of climatic variation and ocean acidification. It was agreed that there are research gaps and hence to put forward a request for advice from ICES to inform the development of OSPAR monitoring tools to detect and quantify the effects of ocean acidification and climate change on species, habitats and ecosystem function, including the identification of suitable species and key areas (OSPAR BDC 2012 SR, Annex 16, §A3).

Supporting information

Priority	The Study Group is established based on a request from OSPAR to further the current activities on Ocean Acidification. Consequently, these activities are considered necessary and to have a very high priority. The expected time frame for the Study group is two to three years.
Scientific justification	The current level of scientific knowledge is not sufficiently developed for monitoring of biological parameters. Data on physical and chemical parameters relating to ocean acidification are a prerequisite for understanding the potential response of biological organisms. At the same time, monitoring of physical and chemical parameters should be informed by susceptibilities of species and habitats, depending on their situation (e.g. biogeographic range). It is, therefore essential that the consideration of biological parameters is taken into account, so that as knowledge advances, this can inform the evolution of monitoring for ocean acidification in an iterative manner.
Resource requirements	The research programmes which provide the main input to this group are already underway, and resources are already committed. The additional resource required to undertake additional activities in the framework of this group is negligible.

Annex 3: Recommendations

Development of coordinated OSPAR monitoring for OA and its impacts

SGOA Recommends that:

MONITORING STRATEGY	TO
The draft OSPAR Agreement on a Common Strategy to Enhance Coordinated Monitoring of Ocean Acidification in the Northeast Atlantic (Annex 5) should be considered by OSPAR for adoption to foster implementation of a flexible long-term monitoring and assessment programme in the OSPAR area.	OSPAR
The OSPAR monitoring programme for OA should be initiated as early as possible to ensure high quality long-term datasets can be generated. The lack of specific biological indicators or assessment criteria at this stage should not impede development of monitoring chemical aspects of OA.	OSPAR
The OSPAR monitoring programme for OA should evolve to maximise coherence with other regional (e.g. US and Arctic) and global OA monitoring developments, to ensure data can be harmonized at a North Atlantic scale and contribute to the Global Ocean Acidification Observing Network.	OSPAR
Where feasible, relevant OA parameters should be routinely added to other existing and planned monitoring activities in the OSPAR area with a view to developing longterm and integrated datasets. This includes adding relevant parameters to monitoring of major river discharges, recognising the importance of Quality Assurance for such waters.	OSPAR CPs
The Arctic should be given special prominence in OSPAR OA-monitoring due to its inherent vulnerability to OA.	OSPAR
BIOLOGICAL INDICATORS	
Further work is required to develop a suite of suitable robust, sensitive, and OA-specific biological impact indicators that have wide biogeographical relevance in the OSPAR area.	OSPAR/ICES
A broad suite of organisms (particularly thecosomate pteropods) likely to be sensitive to OA, should be collected and archived. This archive will serve as a repository of specimens that can be retrospectively examined for evidence of OA responses once appropriate indicator metrics are developed. Appropriate techniques for collection and preservation need to be developed.	ICES WGZE/ OSPAR CPs
QUALITY ASSURANCE TOOLS	
There is an need to develop suitable Certified Reference Materials covering a range of salinities and other water quality conditions.	OSPAR/ICES/monitoring community
Routine proficiency-testing for Total Alkalinity and Dissolved Inorganic Carbon should be initiated to support OSPAR monitoring.	QUASIMEME

Following the OA Quality Assurance workshop scheduled for 2015, other QA issues may require the development of guidelines to support harmonized OA monitoring, for example techniques for preservation of samples and estimation and reporting of uncertainty of measurement.	ICES /OSPAR
DATA HANDLING	
OSPAR OA monitoring data and associated QC and metadata should be reported to the ICES *Environmental database* using formats as stipulated by SGOA and MCWG (ERF 3.2 format for discrete sample data). However, this database is not well suited to collect continuous sensor data e.g. pCO_2. The alternative ICES *Oceanographic database* is at present unsuited to the collection of OSPAR OA monitoring data due to limitations in storing relevant QC/method metadata.	OSPAR CPs
OSPAR Contracting Parties should report relevant riverine input data to the OSPAR RID database.	OSPAR CPs, OSPAR INPUT WG
It is further recommended that OSPAR ocean carbon and metadata are reported to the CDIAC international database, according to the internationally standardised formats. OSPAR data in CDIAC should be flagged as such.	OSPAR CPs
ICES should explore the potential for automated data exchange with CDIAC when suitable data are available. The ICES Data Centre should collaborate with other data centres such as NOAA National Oceanographic Data Centre and CDIAC to develop common data exchange and traceability protocols for OA monitoring data.	ICES-DC, CDIAC, NOAA-NODC and other relevant datacentres

SGOA recommends continuation of an ICES OA expert group as a working group	ICES

Annex 4: Chemical monitoring activities relevant to OA in the OSPAR and HELCOM areas

Table 1. Recent and current carbonate system monitoring activities in the NE Atlantic and Baltic Sea.

COUNTRY/INSTITUTE	PI	AREA	OSPAR/ HELCOM REGION	PLATFORM/TYPE	PARAMETERS	PERIOD
Belgium / ULg	Borges	Southern Bight of North Sea	OSPAR II	RV Belgica (research vessel)	Underway pCO2	2000–on going
Belgium / ULg	Borges	Ste Anna (Scheldt estuary)	OSPAR II	FS Fixed station, continuous	pCO_2	2002–on going
Belgium / ULg	Borges	Celtic Sea	OSPAR III	RV Research cruises, OMEX-II, CCCC, PEACE	pCO_2, TA, pH	1997–1999, 2002, 2004, 2006–2009
Belgium / ULg	Wollast / Chou	Iberian upwelling system	OSPAR IV	RV Research cruises (OMEX-II)	pCO_2, TA, pH	1997–1999
Belgium / ULg / NIOO		RV Luctor monitoring (Scheldt estuary)	OSPAR II	RV monthly cruises	pCO_2 TA	2008–on going
Estonia/	Lipps	Helsinki – Talinn	HELCOM	SOO	Underway pCO_2	2010
Faroe Islands	Nielsdóttir	Faroe Bank Channel, Iceland Ridge, Norwegian Sea, Faroe-Shetland channel	OSPAR I	Time-series 3–4 times annually	TA, TIC, nutrients	2014–on going
France		Plymouth - Roscoff (FERRYBOX Armorique)	OSPAR II	SOO	Underway pCO_2	2010–
France		ASTAN (48°46'N; 3°56'W)	OSPAR II/III?	FS Mooring	pCO_2	2009–

Country/Institute	PI	Area	OSPAR/ HELCOM region	Platform/type	Parameters	Period
France / Ifremer		MAREL Iroise (48°22'N; 4°33'W)	OSPAR II	FS Mooring	pCO_2, pH	2003–
France / Ifremer		MAREL Carnot (50°44.71'N; 1°34.18'W)	OSPAR II	FS Mooring	pH	2004–
France / Ifremer		MAREL La Tremblade - Marennes Oléron	OSPAR II	FS Mooring	pH	
France / EDF		Cordemais (Loire Estuary)	OSPAR IV	FS Mooring	pH	2005–
France / CNRS - INSU	Patrick Raimbault (patrick.raimbault@univmed.fr)	MOOSE (DYFAMED, ANTARES, MOLA) - Mediterranean Sea	Barcelona Convention	Niskin bottles RV monthly or annually cruises	pH, DIC, carbon flow	1995– (DYFAMED) 2003– (MOLA) 2005– (ANTARES)
France	Benoit Sautour (b.sautour@epoc.u-bordeaux1.fr)	SOMLIT - English Channel, Atlantic Ocean and Mediterranean Sea	OSPAR II, IV Barcelona Convention	SO	pH	1984– according to station
France	Nathalie Simon (Nathalie.Simon@sb-roscoff.fr)	RESOMAR-PELAGOS - English Channel, Atlantic Ocean and Mediterranean Sea	OSPAR II, IV Barcelona Convention	SO	pH	1987– according to station
France / AAMP - PNMI	Patrick Pouline (patrick-pouline@aires-marines.fr) Pascale-Emmanuelle Lapernat (pascale-emmanuelle.lapernat@aires-marines.fr)	PNMI - Iroise Sea	OSPAR II	SO RV cruises three/year	pH	2010–

Country/Institute	PI	Area	OSPAR/ HELCOM region	Platform/type	Parameters	Period
France		RNF (Seine estuary, Bouches de Bonifaccio)	OSPAR II Barcelona Convention	Seine : monthly measure Bonifaccio : RV cruises four/year during summer	pH	
France / GIP Seine-Aval	Céline Dégremont (cdegremont@seine-aval.fr) Loïc Guézennec (lguezennec@seine-aval.fr)	SYNAPSES (Seine Estuary)	OSPAR II	FS Mooring	pH	2011–
France LOCEAN	Lefevre	France – French Guiana	?	SOO (MN Colibri) ~six/year	Underway pCO_2	2006–
France LOCEAN	Lefevre	France – Brazil	?	SOO (Monte Olivia) ~six/year	Underway pCO_2	2007–
Germany	Weigelt-Krenz/BSH	German Bight	OSPAR II	National monitoring programme (four times/year)	pH /continuous pH measurements/nutrients/ TA (2014–)	1990– 2011–
Germany	Weigelt-Krenz/BSH	Helgoland	OSPARII	Measurement station	continuous pCO_2 measurements	July 2013
Germany		Irregular		RV Polarstern	Underway pCO_2	
Germany / AWI?		Nordic Seas (Greenland Sea?)	OSPAR I	RV Research cruises	?	?
Germany / IFM-GEOMAR		Boknis Eck (54.52°.N 10.03° E)		FS Time-series station	?	?
Germany / IOW	Schneider now Reider	Helsinki – Lübeck		SOO	Underway pCO_2	
Germany IFMGeomar Kiel	Koertzinger/Wallace	Liverpool - Halifax	OSPAR V	SOO (A. Companion)	two per five weeks Underway pCO_2	2005
Iceland / MRI	Olafsson /Olafsdottir	Iceland Sea & Irminger Sea	OSPAR I	FS Single time-series stations	DIC, discrete pCO_2, pH	from 1983

COUNTRY/INSTITUTE	PI	AREA	OSPAR/ HELCOM REGION	PLATFORM/TYPE	PARAMETERS	PERIOD
Iceland / MRI	Olafsson Olafsdottir	Icelandic waters and the Iceland Sea	OSPAR I	RV Bjarni Saemundsson	Underway pCO_2	from 1995
Ireland / MI & NUI Galway	Ward	Irish Shelf and off-shelf	OSPAR III & V	RV Celtic Explorer	Underway pCO_2	2009–2011
Ireland / MI & NUI Galway	O'Dowd/Ward	Mace Head Coastal Atmospheric research station	OSPAR III	FS Buoy	pCO_2	2008–2009
Ireland / NUI Galway & MI	McGovern / Cave	Irish Shelf and off-shelf	OSPAR III & V	RV Research Cruises	TA, DIC	2008–
Ireland / NUI Galway & MI	McGovern / Cave	Rockall Trough Winter Transects	OSPAR V	RV Celtic Explorer	TA, DIC	2008–
Netherlands / NIOZ	de Baar	Basinwide North Sea	OSPAR II	RV Research cruises	DIC pCO_2 (TA)	2001, 2005, 2008, 2011
Netherlands / NIOZ		Southern Bight of the North Sea / German Bight	OSPAR II	NIOZ jetty (53°N; 4° 46'E) Weekly to monthly time-series	DIC, TA	2008–2010
Netherlands	Houben	North Sea	OSPAR II	Research vessel	pH	ongoing
Norway/ IMR	Chierici	Torungen - Hirtshals	North Sea	IMR research vessels	water column DIC, TA, nutrients	start 2010–2012, 2–4 times annually: 2013–2016: 1/year
Norway/ IMR	Chierici	Gimsøy-NW	Norwegian Sea	IMR research vessels	water column DIC, TA, nutrients	start 2010–2012, 2–4 times annually: 2013–2016: 1/year

Country/Institute	PI	Area	OSPAR/ HELCOM REGION	Platform/type	Parameters	Period
Norway/ IMR	Chierici	Svinøy-NW	Norwegian Sea	IMR research vessels	water column DIC, TA, nutrients	start 2010–2012, 2–4 times annually: 2013–2016: 1/year
Norway/ IMR	Chierici	Fugløya-Bjørnøya	Barents Sea (SW)	IMR research vessels	water column DIC, TA, nutrients	start 2010–2012, 2–4 times annually: 2013–2016: 1/year
Norway/ IMR	Chierici	Bjørnøya-Sørkapp	Barents Sea (SW)	IMR research vessels	water column DIC, TA, nutrients	start 2013 to 2016: 1/year
Norway/ IMR	Chierici	Vardø-N	Barents Sea (NE)	IMR research vessels	water column DIC, TA, nutrients	start 2010–2012, 2–4 times annually: 2013–2016: 1/year
Norway/ IMR & FRAM centre (OA Flagship)	Chierici/Fransson (NPI)	Fram Strait	Arctic Ocean/Greenland Sea	RV Lance	water column DIC, TA, nutrients	start 2011 ongoing
Norway/ IMR & FRAM centre (OA Flagship)	Chierici/Fransson (NPI)	N of Svalbard to Polar Basin, 81-82N, 30E	Arctic Ocean	RV Lance	water column DIC, TA, nutrients	start 2012 on going. 1/year
Norway / UiB & Bjerknes	Johannessen	75° N transect	OSPAR I	RV Research cruises	DIC, TA	2003, 2006, 2008?
Norway / UiB & Bjerknes	Skjelvan/Johannessen	OWS M	OSPAR I	FS WS Monthly profiles	DIC, TA	2001–2009

COUNTRY/INSTITUTE	PI	AREA	OSPAR/ HELCOM REGION	PLATFORM/TYPE	PARAMETERS	PERIOD
Norway / UiB & Bjerknes	Skjelvan/Johannessen	OWS M	OSPAR I	FS WS Continuous	pCO_2	2005–2009
Norway / UiB & Bjerknes	Skjelvan/Johannessen	OWS M	OSPAR I	FS Buoy Continuous	pCO_2	2011
Norway / UiB & Bjerknes	Johannessen/Olsen/Lauvset	Nordic Seas	OSPAR I	RV G. O. Sars (research vessel)	Underway pCO_2	ongoing
Norway / UiB & Bjerknes	Johannessen/Olsen/Omar	Aarhus – Nuuk		SOO (Nuka Arctica)	Underway pCO_2	2005–
Norway / UiB & Bjerknes	Johannessen/Omar	Bergen – Amsterdam	OSPAR II	SOO / weekly	Underway pCO_2	2005–2009
Norway / UiB & Bjerknes	Johannessen/Omar	North sea	Sleipner	RV G. O. SARS	Underway pCO_2	June 2012
Norway / UiB & Bjerknes	Johannessen/Omar	North sea	Sleipner	RV G. O. SARS	TA, DIC	June 2012
Norway NIVA	Sorensen	line up to Svalbard	Ferry-box	SOO	Underway pCO_2	2012
Portugal/IPMA	Nogueira	West and South Portugal Coast, Continental platform	OSPAR IV	RV Research cruise, April	pH, DIC, TA and underway pCO_2	2013
Portugal/IPMA	Nogueira	Douro estuary adjacent coast (40.54-41.30ºN; 8.45-9.20ºW)	OSPAR IV	Scientific cruise	pH, DIC, TA, pCO_2	2004
Portugal/IPMA	Nogueira	Tagus and Sado estuary adjacent coast (38.15-38.45ºN; 8.51-9.36ºW)	OSPAR IV	Scientific cruises	pH, DIC, TA, pCO_2	one per year 1999–2007

COUNTRY/INSTITUTE	PI	AREA	OSPAR/ HELCOM REGION	PLATFORM/TYPE	PARAMETERS	PERIOD
Spain / IIM	Perez / Rios	OVIDE, Iberian Peninsula-Greenland	OSPAR V	RV Research cruise	Underway pCO_2, pH,TA	2002–2012
Spain / IIM	Rios / Perez	FICARAM, Spain-Antarctic	OSPAR V	SOO	Underway pCO_2, pH, TA	2001, 2002, 2013
Spain / ULPGC	Davila	English Channel – Durban	OSPAR V	SOO various ships	Underway pCO_2	2005
Spain / ULPGC	Davila	ESTOC Station	Canary Islands	FS Time-series	pCO_2, TA, pH	1996–
Spain / ULPGC	Santana Casiano	Greenland-Scotland 59.5ºN	OSPAR V	RV Russian Research cruise	pH, TA, TIC	2009–2012
Spain ICMAN	Huertas	Gulf of Cadiz	OSPAR IV	RV P3A2 Cruises	pH, TA	2003–2008
Spain ICMAN/IIM/IEO	Huertas	Strait of Gibraltar (35.862°N, 5974°W)	OSPAR IV	FS Mooring	pCO_2, pH	2011–
Spain ICMAN/IIM/IEO	Huertas	GIFT (35.862°N, 5.974°W; 35.957ºN, 5.742°W; 35.985ºN, 5.368ºW)	OSPAR IV	FS Time-series stations	Water column pH, TA	2005–
Spain IEO / IIM	Rios	Cantabric Sea and west coast	OSPAR IV	RV VACLAN cruises	Underway pCO_2, pH, TA	2005, 2007, 2009
Spain IEO-Gijon	Scharek	Cantabric Sea	OSPAR IV	FS Time-series (three stations)	pH, TA	2010–2011
Sweden/SMHI		Swedish waters	Baltic, OSPAR II	Monitoring cruises	pH, TA	1990–
Sweden/SMHI	Karlson	Gothenburg-Kemi	Baltic	SOO	underway pCO_2, TA	2010–2014
Sweden/SMHI	Karlson	Gothenburg-Kemi	Baltic	SOO	underway pCO_2	2010–
Sweden/University of Gothenburg		Arctic ocean	OSPAR I	RV Research cruise	DIC, pH, TA	2005, 2014
UK / Cefas	Greenwood /Pearce	Liverpool Bay	OSPAR III	Buoy, DEFRA tests	pCO_2	2010

COUNTRY/INSTITUTE	PI	AREA	OSPAR/ HELCOM REGION	PLATFORM/TYPE	PARAMETERS	PERIOD
UK / Cefas	Greenwood /Pearce	Irish Sea and Celtic Sea	OSPAR III	RV Research cruises	DIC, TA and underway pCO_2	2011–
UK/MSS	Walsham	Stonehaven	Coastal site/ OSPAR II	FS Weekly single time-series station	TA/DIC	2008–
UK / MSS	Walsham	Faroe Shetland Channel, Atlantic inflow to North Sea	OSPAR I & II	RV Research cruise, May and Dec	TA/DIC, hydrography	2012–
UK / MSS / NOC:	Walsham		OSPAR I, II, III & V	RV Scotia	Underway pCO_2	2014
UK / NOCS	Hydes	English Channel	OSPAR II	SOO (Pride of Bilbao)	DIC, TA	2005–2010
UK / NOCS	Lampitt	Porcupine Abyssal Plain (49°N; 16.5°W)	OSPAR V	RV Mooring	pCO_2, pH	2009–
UK / NOCS	Hydes	Portsmouth - Spain	OSPAR II & IV	SOO (Pride of BIlbao), 2/week	Underway pCO_2	2005–2010
UK / PML	Mountford / Kitidis	Holyhead – Dublin,	OSPAR III	RV Prince Madog (research	Underway pCO_2	2006–2009
UK / PML	Mountford / Kitidis	Irish Sea Coastal Observatory	OSPAR III ?	RV (quasi-monthly)	Underway pCO_2 Transects (Prince Madog)	2007–2010
UK / UEA	Schuster	Portsmouth (UK) Windward Islands -	?	SOO (Santa Lucia/Santa Maria)	Underway pCO_2	Monthly from 2002–
UK /PML	Mountford / Kitidis	English Channel (E1, L4)	OSPAR II	Weekly (L4) & monthly (E1)	TA/DIC	2008–
UK /PML	Mountford / Kitidis	English Channel (E1, L4)	OSPAR II	Weekly (L4) & monthly (E1)	Underway pCO_2 Transects (Plymouth Quest)	
UK “Ellett Line”	Reid / Hartman	Greenland – UK	OSPAR I & III	Scientific cruise	Hydrography	Once yearly 2008, 2010–

COUNTRY/INSTITUTE	PI	AREA	OSPAR/ HELCOM REGION	PLATFORM/TYPE	PARAMETERS	PERIOD
UK/Cefas	Greenwood /Pearce	Basinwide North Sea and English channel	OSPAR II	RV Research cruises RV Endeavour	DIC, TA and underway pCO_2	2011–
USA / France	Metzel	Charleston – Reykjavik	?	SOO (Reykjafoss)	Underway pCO_2	From 2005

Note: Reproduced from Hydes *et al.*, 2013 and updated most recently at SGOA 2014. This table is based on information received by MCWG and SGOA and does not purport to be definitive or complete.

Annex 5: Draft OSPAR Ocean Acidification Monitoring Strategy

DRAFT OSPAR Agreement on a Common Strategy to enhance Coordinated Monitoring of Ocean Acidification in the North-East Atlantic

1. Background and Policy Context

1.1 The IPCC defined ocean acidification:

Ocean acidification refers to a reduction in the pH of the ocean over an extended period, typically decades or longer, which is caused primarily by uptake of carbon dioxide from the atmosphere, but can also be caused by other chemical additions or subtractions from the ocean. Anthropogenic ocean acidification refers to the component of pH reduction that is caused by human activity (IPCC, 2011).

1.2 With respect to the monitoring and assessment of Climate Change and Ocean Acidification, the Northeast Atlantic Strategy indicates that the OSPAR Commission will:

- monitor and assess the nature, rate and extent of the effects of climate change and ocean acidification on the marine environment and consider appropriate ways of responding to those developments. Considerations of the impacts of climate change and ocean acidification, as well as the need for adaptation and mitigation, will be integrated in all aspects of the work. The OSPAR Commission will work with partner organisations (such as the International Council for Exploration of the Sea (ICES), the Intergovernmental Oceanographic Commission (IOC) and the Arctic Council) to enhance the knowledge of these issues (1.7);
- assess, based on monitoring data, the current and future impacts of climate change and ocean acidification on species, habitats and ecosystem functioning; establish the time-scale(s) for such impacts to take effect and their possible extent; and consider management options suitable for mitigation of, and adaptation to, such impacts (4.2 c).

1.3 The OSPAR Quality Status Report 2010 (OSPAR 2010) recognised that "rising sea temperature and acidification represent major threats to marine ecosystems in the OSPAR area". The OSPAR Bergen Statement also stated that "We respond to new challenges and priorities, such as facilitating the implementation of the EU MSFD(sic), and addressing the challenges of climate change and ocean acidification". The Bergen Statement also expanded to say:

"31. We note with deep concern the impacts of climate change and ocean acidification, which are predicted to profoundly affect the productivity, biodiversity and socio-economic value of marine ecosystems. We emphasise that research into and considerations of these effects, as well as the need for adaptation and mitigation, will have to be integrated in all aspects of our work. We affirm that there is a role for the OSPAR Commission, in collaboration with other international organisations, in investigating, monitoring and assessing the rate and extent of these effects and considering appropriate responses."

1.4 Ocean Acidification has clearest links with OSPAR's Thematic Strategies on Biodiversity and Eutrophication. The latter may be a driver of anthropogenic acidification in inshore waters and there are potential synergies in monitoring eutrophication and acidification in these environments.

1.5 Ocean Acidification and Climate Change are included in Theme A of the OSPAR Joint Assessment and Monitoring Programme (JAMP) (OSPAR

2014a). Monitoring of carbonate system parameters has been included in the OSPAR pre-CEMP since 2012, indicating voluntary monitoring. OSPAR technical guidelines for monitoring the Chemical Aspects of Ocean Acidification have been adopted by OSPAR (OSPAR 2014b).

1.6 In 2010, in response to an OSPAR request for advice, ICES provided advice on Monitoring Methodologies for Ocean Acidification. This noted that "*a coordinated ocean acidification (OA) monitoring programme is needed that integrates physical, biogeochemical, and biological measurements to concurrently observe the variability and trends in ocean carbon chemistry and evaluate species and ecosystems response to this changes. For the physico-chemical parameters there is a good basis for initiating monitoring although there are some technical issues that still need to be resolved. However, the science needed to develop a monitoring programme for impacts of ocean acidification is less developed…*" It was also noted that there are several sustained projects and programmes that can be utilised or built on to develop a monitoring network for the ICES area and that such monitoring should be strongly linked with global observational networks. (ICES 2010, Hydes *et al.*, 2013).

1.7 A joint OSPAR-ICES Study Group on Ocean Acidification (SGOA) was established in 2012 with a number of Terms of Reference related to development of monitoring and assessment.

1.8 In response to the need for a worldwide OA observation network (Feely *et al.*, 2010), the Global Ocean Acidification-Observing Network (GOA-ON) (Newton *et al.*, 2014) was established. The OSPAR strategy for OA Monitoring can be viewed as a regional contributing component of GOA-ON and draws on principles outlined in the GOA-ON, noting that this is an evolving process.

1.9 Other monitoring and/or assessment initiatives of relevance in North Atlantic include those of the Arctic Monitoring and Assessment Programme (AMAP) and US strategic plan for federal research and monitoring (IWG-OA 2014).

2. Principles and Considerations

The following principles and considerations frame the monitoring strategy.

- OA is a stressor that requires a long-term monitoring strategy and commitment so as to distinguish long-term (multidecadal) anthropogenic signals from short- and medium-term spatial and temporal variability.
- This monitoring strategy is envisaged as a flexible framework. It is essential that the monitoring network is responsive to developments in scientific knowledge, emerging tools and technology, and remain consistent with advances in the global observation network.
- As well as characterising long-term changes to the carbonate system, monitoring should characterise spatial variability and temporal variability on shorter time-scales. Monitoring will need to identify deviations to the range of variability that may be ecologically relevant, for example, seasonal changes in spatial and/or temporal extent of seasonal saturation states. Moreover, marine ecosystems are subject to a variety of concurrent pressures such as warming, eutrophication, hypoxia, and pollution, which may act in concert to produce responses that may be additive, synergistic or antagonistic. In recent years research has begun to focus on the potential interaction of OA with other stressors, and in particular with ocean warming. This should be taken into account when selecting variables to monitor and assess ecosystem health and where possible combined monitoring relating to multiple pressures/stresses should be undertaken.
- Monitoring of the response of ecosystems, and the services they provide, to OA should ideally consider all levels of ecosystem organisation in an integrated manner. Thus, monitoring could ultimately incorporate responses at subcellular, morphology/pathology, whole-organism, population and community levels as may be deemed appropriate.
- The development of appropriate biological indicators for OA, especially robust indicators that are sensitive and OA-specific and broadly applicable across wide biogeographic areas is at a very early stage and further development is required before recommendations can be given.
- While some areas may be inherently more vulnerable, OA is a threat to all marine ecosystems, with CO_2 taken up by surface oceans subsequently penetrating deep oceans. While the strategy should emphasise monitoring of the most vulnerable areas, which should provide clearest and earliest signals of change, monitoring should represent the full OSPAR maritime area.
- In this regard, the Arctic Ocean is particularly sensitive to OA and is expected to show widespread calcium carbonate undersaturation conditions earlier than other oceans (Steinacher *et al.*, 2009; AMAP 2013). Colder and fresher water means it is more susceptible to CO_2 uptake but less well buffered than temperate oceans. Other aspects contributing to this vulnerability include additional carbon sources (methane and organic carbon inputs) and the low biodiversity and simple foodwebs that characterise the Arctic.

Some practical considerations that will further guide monitoring are:

- In so far as possible OA monitoring should leverage available infrastructure and monitoring assets to support cost-effective monitoring and to supply integrated datasets.
- OA monitoring requires an interdisciplinary approach. For instance understanding of the hydrodynamic context is critical to understanding local and regional aspects, while knowledge of 'natural' variability in species' abundance is also crucial to interpreting ecosystem responses. Such factors should be considered in monitoring programme design.
- Modelling will become increasingly important as monitoring data should support validation/calibration of predictive models and models will in turn provide tools for design of monitoring.

3. Purpose of Monitoring

3.1 The purpose of the OSPAR OA monitoring strategy is to document the spatial and temporal changes in the CO_2-driven changes in ocean biogeochemistry in the OSPAR region and to detect and interpret ecosystem responses to these perturbations. The information gathered through such monitoring is essential to develop an understanding, and inform projections, of both ecosystem and socio-economic responses. Monitoring and assessment outputs should inform policy development and provide products that will simply and effectively communicate the key issues at an appropriate level to a wide range of stakeholders, including the public.

3.2 The specific goals of the monitoring programme were considered to be twofold. **Goal 1** is to determine the spatio-temporal pattern of biogeochemical conditions relating to OA throughout the OSPAR region, while **Goal 2** involves characterisation of the ecosystem responses to OA in time and space.

Achieving Goal 1 (OA conditions) requires

- Documentation and evaluation of spatial and temporal variation in carbon chemistry to infer mechanisms (including biological mechanisms) driving OA; and
- Information of sufficient spatial and temporal resolution to underpin the identification of biological impacts, identify areas of potential vulnerability or resilience, and future ecological risks, through direct observation and the use of numerical models.

Achieving Goal 2 (ecosystem response) requires

- That biological responses, and their socio-economic consequences, be tracked in concert with physical/chemical changes; and
- Rates of change are quantified and locations/habitats and species of heightened vulnerability or resilience identified.

4. OA Monitoring Framework

4.1 The monitoring programme outlined defines requirements to cover the spectrum from the **open ocean** to **coastal waters (including estuaries)**. Anthropogenic CO_2 emissions may be considered the primary driver of ocean acidification in the "Open Ocean" due to uptake of increasing levels of atmospheric CO_2. In coastal waters, many local or regional drivers, which may themselves be linked to human activities, can also modulate pH trends. These include changes in nutrient inputs; watershed export of alkalinity and carbon; and ecosystem structure and processes (Cai *et al.*, 2011; Duarte *et al.*, 2013). Local/regional management options may be available to address these multiple drivers. Monitoring in coastal ecosystems needs to consider multiple drivers of pH variability and responses.

4.2 **Goal 1** and **Goal 2** monitoring variables are grouped as ***Level 1*** (core set of measurements) and ***Level 2*** (extended suite of measurements) broadly aligning with the conceptual approach elaborated in the GOA-ON framework.

4.3 Goal 1 monitoring – OA Conditions:

4.3.1 Goal 1 parameters are, in essence, physical and biogeochemical variables. Two primary metrics of interest for assessments of temporal and spatial variability are pH and aragonite/calcite saturation states (Ω). Other metrics such as carbonate ion concentrations may also be useful to assist interpretation. To fully constrain the carbon system at least two, and preferably three, of the following parameters should be determined: pCO_2, Dissolved Inorganic Carbon (DIC), Total Alkalinity (TA) and pH. The **Goal 1** monitoring variables are presented in Table 1. OSPAR JAMP OA monitoring guidelines provide further details. (OSPAR 2014b).

4.3.2 Monitoring to determine spatial and temporal trends is likely to incorporate data collected using a variety of platforms including shipboard cruises such as research vessels, voluntary observing ships (VOS), fixed platforms (e.g. moorings) and novel mobile platforms (e.g. gliders and floats). While sensors on fixed and mobile platforms provide the possibility for high temporal and spatial resolution, the data objectives for OA-"climate" monitoring (see section 5) and requirements for a wider range of parameters still requires ship-based discrete sampling and analysis at key stations/sections. However, it is anticipated that technological developments will lead to an increased emphasis on sensors providing much improved spatial and temporal resolution.

4.3.3 For the open ocean, repeat hydrography surveys (e.g. GO-SHIP), VOS and ocean time-series will provide a basis for ongoing monitoring and continuation and expansion of these activities should be supported. For marginal seas and coastal areas, linking with OSPAR eutrophication monitoring, or fisheries assessments, may provide a cost-effective monitoring approach in some locations.

4.3.4 OA-relevant parameters should be included in riverine input(s) monitoring as part of the OSPAR RID programme for major rivers discharging into OSPAR coastal waters.

4.3.5 For Goal 1 data high spatial and temporal frequency data are required to describe the variability of the systems. However, for ship-based surveys, monitoring during periods of lowest biological activity and deepest mixing (winter) is of most use to establish long-term trends for the surface ocean.

Table 1. Initial proposals of SGOA for core measurements and extended suite of measurements that may be incorporated in OSPAR Ocean Acidification (OA) monitoring programme for Goal 1 monitoring of open ocean, coastal and estuarine waters.

GOAL 1	TRACKING OA CONDITIONS AND CHANGES
Key Assessment variables	Ω, pH, CO_3^{2-}
Core Measurements (Level 1)	Carbonate-System Constraints (2 of 4 – pCO_2, DIC, TA, pH)*,T, S, DO, Dissolved inorganic nutrient (PO4,SiO4,TOxN)**, Fluorescence, pressure
Extended Suite of Measurements (Level 2) §	Carbon System Constraints (3 of 4- pCO_2, DIC, TA, pH), and others such as DOM[b], bio-optical (PAR, turbidity), · transient water mass tracers[a], particulate carbon (PIC:POC), ^{18}O[b]
Where:	Surface open ocean, mode and deep-water, shelf edge, shelf seas, coastal waters, estuaries (all OSPAR regions), Note particular emphasis required for high latitudes due to more rapid rates of acidification
How	Hydrographic Surveys, ecosystem /fisheries surveys, VOS, Moorings, MSFD monitoring for pelagic habitats where appropriate Where possible OA parameters should be included in Eutrophication[b] Include TA/DIC in Riverine Input monitoring for major rivers[b].
Timing/Frequency	Ideally capture seasonal variability but winter key period for surface waters for long-term trend assessment[a]. High frequency monitoring to determine natural variability and seasonal aspects emphasis on winter for trend[b].

[a] Open ocean, [b] coastal and estuarine waters.

***In some cases for offshore waters TA may be calculated from appropriate algorithms e.g. Lee *et al.*, 2006; Nondal *et al.*, 2009.**

****It is recognised that nutrients won't be available for some monitoring platforms.**

§ Other additional variables that should be considered are Goal 1 Level 2 parameters listed in GOA-ON report (Newton *et al.*, 2014) essential variables.

4.4 Goal 2: Monitoring Ecosystem Response:

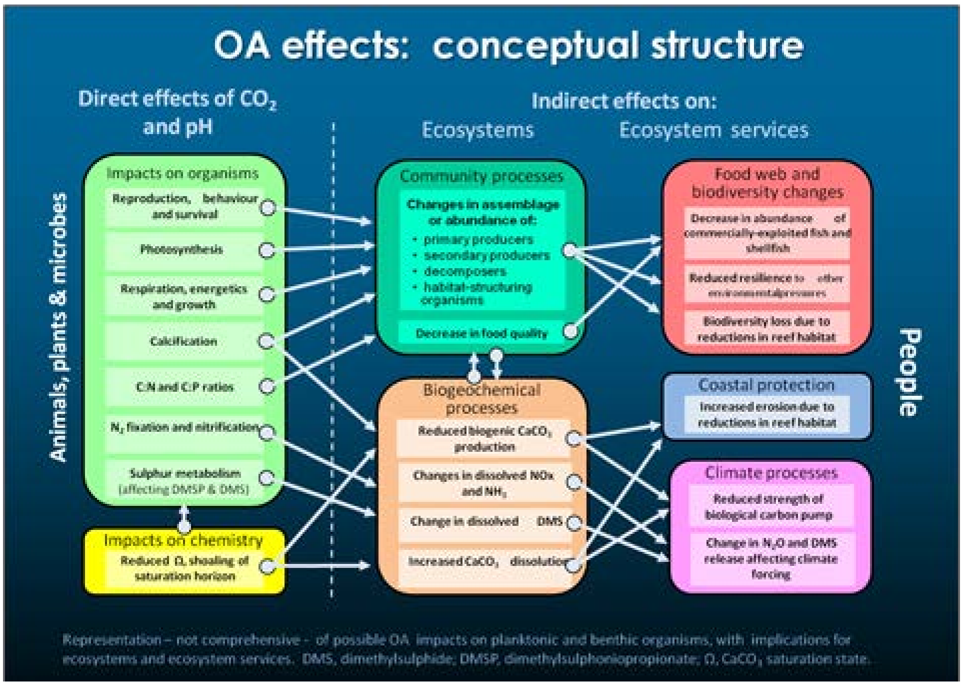
4.4.1 Figure 1 provides an overview of potential direct and indirect ecosystem responses. Moreover, ecosystem processes in themselves have feedbacks on ocean chemistry, for example draw down of alkalinity due to blooms of pelagic calcifiers.

4.4.2 Monitoring tools to determine the impacts of OA are at a very early stage of development. Consequently, only broad advice on appropriate indicators of general ecosystem health (e.g. biomass of functional groups such as phytoplankton, zooplankton, and benthos) can be given. Moreover, it is important to recognise that observed changes are likely to be due to multiple stressors rather than OA alone. In the absence of sufficient data to provide guidance on specific species that are likely to be sensitive to OA, a list of taxa for which there is published data documenting responses to OA in either laboratory or field studies is given in Table 2.

4.4.3 OA conditions (Goal 1 variables) should be measured concurrently at stations sampled for Goal 2. In advance of clear guidance on Goal 2 variables, adding Goal 1 chemical measurements to relevant biological monitoring series undertaken for other purposes. For example, OSPAR/Marine Strategy Framework Directive (MSFD) core indicators for plankton would be a useful starting point to generate integrated datasets.

4.4.4 It is further recommended that a broad suite of organisms likely to be sensitive to OA, for example thecosomate pteropods (e.g. *Limacina helicina* in the Arctic region), be collected and archived during the initial OA monitoring programme. This archive will serve as a repository of specimens that can be retrospectively examined for evidence of OA responses once appropriate indicator metrics are developed. It is essential that experts familiar with the target organisms be consulted prior to collection and archival because current archival protocols (e.g. formalin) may be inadequate for preservation of anatomical structures potentially sensitive to OA.

4.4.5 Impact indicators may be specific for vulnerable areas/species/habitats but may also include indicators related to socio-economic impact.



OA effects: conceptual structure

Representation – not comprehensive - of possible OA impacts on planktonic and benthic organisms, with implications for ecosystems and ecosystem services. DMS, dimethylsulphide; DMSP, dimethylsulphoniopropionate; Ω, CaCO3 saturation state.

Figure 1. Conceptual model of the effects of OA on ecosystems illustrating direct effects of CO_2 and pH on organisms, as well as indirect effects of OA on ecosystems and ecosystem services (adapted from Williamson and Turley, 2012).

Table 2. Potential indicator organisms for OA responses, requiring further expert consideration. This list represents initial thoughts; it is not exhaustive, and very different recommendations for indicator species may subsequently be developed. (Table is reproduced from Final SGOA Report to OSPAR Section 7).

GROUP	SPECIES	QUANTITATIVE BASIS FOR USE AS INDICATOR?	ISSUES/COMMENTS
Benthic			
Cold-water corals	*Lophelia pertusa*, *Madrepora* spp., *Solenosmilla* spp., *Eunicella* spp.	Slowed growth/mortality at lower depth limit, in response to raising of saturation horizon.	Mortalities may be difficult to determine without high resolution repeat ROV/AUV mapping of specific study sites. Development of morphological indices based on skeletal metrics would be necessary to document erosion/reduced or altered deposition.
Echinoderms (particularly some brittlestar species)	Some brittlestar species e.g. *Ophiothrix fragilis*	Reduced abundance (taking account of other factors) and lowered larval calcification.	*O. fragilis* particularly sensitive to OA under experimental conditions 100% larval mortality in response to pH decrease of 0.2.
Coralline Macroalgae	*Lithothamnion gracile* *L. corallioides*, *Phymatolithon calcareum*, *Lithophyllum dentatum*	Growth rate (using annual rings and changes in boron isotope composition)	Morphological techniques being developed; sensitivity to OA uncertain.
Non-Coralline Macroalgae		Increased productivity.	
Molluscs	*Littorina littorea*	Currently monitored in Dutch waters as part of OSPAR eutrophication monitoring.	Lab studies indicated reduced calcification under elevated pCO_2.
	Mytilus spp.	Currently monitored as part of contaminant assessment.	Reduced shell and byssus strength when grown under experimental treatments with elevated pCO_2 though some wild populations appear healthy undere reduced ph/high-food condition.
Calcareous Annelids (*Serpulids*)	*Serpula*	Changes tube composition (calcite/aragonite ratio, Mg/Ca ratio) in undersaturated water.	Requires special techniques.
Calcareous epiphytes and epibionts on seagrasses		i) Coverage on seagrasses (abundance) ii) $CaCO_3$ weight	Sensitive to CO_2, but restricted to areas with seagrass.
Seagrasses		Increased abundance, but unlikely to be unambiguously linked to OA	Might benefit from increased CO_2, but this response depends on other environmental conditions

GROUP	SPECIES	QUANTITATIVE BASIS FOR USE AS INDICATOR?	ISSUES/COMMENTS
Crustaceans	*Lobster (Homarus gammarus),* Crabs (*Hyas araneus*, *Cancer pagurus*)	Carapace deformities. Reduced thermal tolerance and scope for activity.	Carapace deformation in larval and juvenile lobsters exposed to elevated pCO_2 at different temperatures
Water column			
Pteropods (planktonic sea snails)	*Limacina* spp and other shelled pteropods	Abundance (taking account of other factors) Shell thickness/condition	High sensitivity to OA under experimental conditions; shell dissolution of *Limacina helicina antarctica* observed in response to existing pH variability of Southern Ocean.
Coccolithophores	*Emiliana huxleyii* and other species.	Abundance and biodiversity (taking account of other factors) Calcification Coccolith morphology/mass/malformation	Unsuitable. Coccolithophore calcification and photosynthesis response to ocean acidification is diverse, species- and even strain- specific. *Emiliania huxleyi* is probably unsuitable as an indicator; the genome variability within this species complex seems to underpin its capacity to thrive under a wide variety of environmental conditions. However, negative effects for *E. huxleyi* population, become evident at elevated CO2 levels projected for this century. Suitability of other species warrants further study. Recent studies highlighted the importance of seawater carbonate chemistry, especially CO_3^{2-}, in unraveling the distribution of heterococcolithophores, the most abundant coccolithophore life phase. A first study based in CO_2 vents showed a decrease in biodiversity in elevated CO_2 conditions.
Foraminifera	Variety of pelagic taxa (also benthic taxa)	Shell morphology/thickness	Relevant features that might be suitable for quantitative assessment currently under investigation. Long time-series potential given their presence in both historical and palaeo observations.
Bivalve larvae	Commercially cultivated species	Larval survival Calcification [both for mariculture conditions]	Risk of OA impacts on cultivated shellfish lower in Europe than in NW USA (the latter subject to strong upwelling of lower pH water) but routine chemical and biological monitoring of aquaculture facilities would nevertheless be desirable.
Phytoplankton	Range of species	Increased productivity. Abundance changes unlikely to be unambiguously linked to OA, but change in C:N ratio may be detectable	Unsuitable. Resolving impacts due to OA will be extremely difficult given their response to other hydrological, biological, and chemical factors. Rapid capacity to modify ambient chemical conditions.

4.5 A cyclical approach to monitoring is proposed as illustrated in Figure 2.

4.5.1 **First Cycle** (suggested six years to tie in with OSPAR/MSFD assessment cycles) should be primarily aimed at establishing competencies and Quality Control (QC) tools for carbonate chemistry monitoring and for providing a current reference against which future changes can be assessed requiring good spatial and seasonal coverage. This requires that consistent and reliable quality standards are achieved for measurements.

4.5.2 Following this phase of monitoring, Contracting Parties should identify areas of heightened vulnerability to OA for more intensive monitoring. These areas should be prioritised for monitoring under Goals 1 and 2 to document change to ocean chemistry and ecosystems. Such areas would have one or more of the following attributes.

4.5.2.1 More rapid rate of acidification for example driven by cold-water temperatures, freshwater input changes, low buffering capacity, specific hydrodynamics such as upwelling of CO_2-rich waters, and/or subject to other drivers of acidification such as eutrophication;

4.5.2.2 Contain particularly susceptible ecosystems, species and/or habitats;

4.5.2.3 A high socio-economic dependence on marine ecosystem services.

4.5.3 **Second and subsequent cycles**:

4.5.3.1 ***Areas of heightened vulnerability***: More intensive monitoring of vulnerable areas identified will focus on Goal 1 (OA conditions) and Goal 2 (ecosystem response). A specific monitoring plan for each area should be prepared taking account of the specific vulnerabilities and considering Goal 1 and 2, level 1 and 2 variables.

4.5.3.2 Other representative areas: Given that OA is a pervasive issue, surveillance monitoring should be continued to determine acidification trends and variability across all OSPAR waters. The primary focus would be on Goal 1 monitoring although selected locations should be tested for a broader suite of parameters.

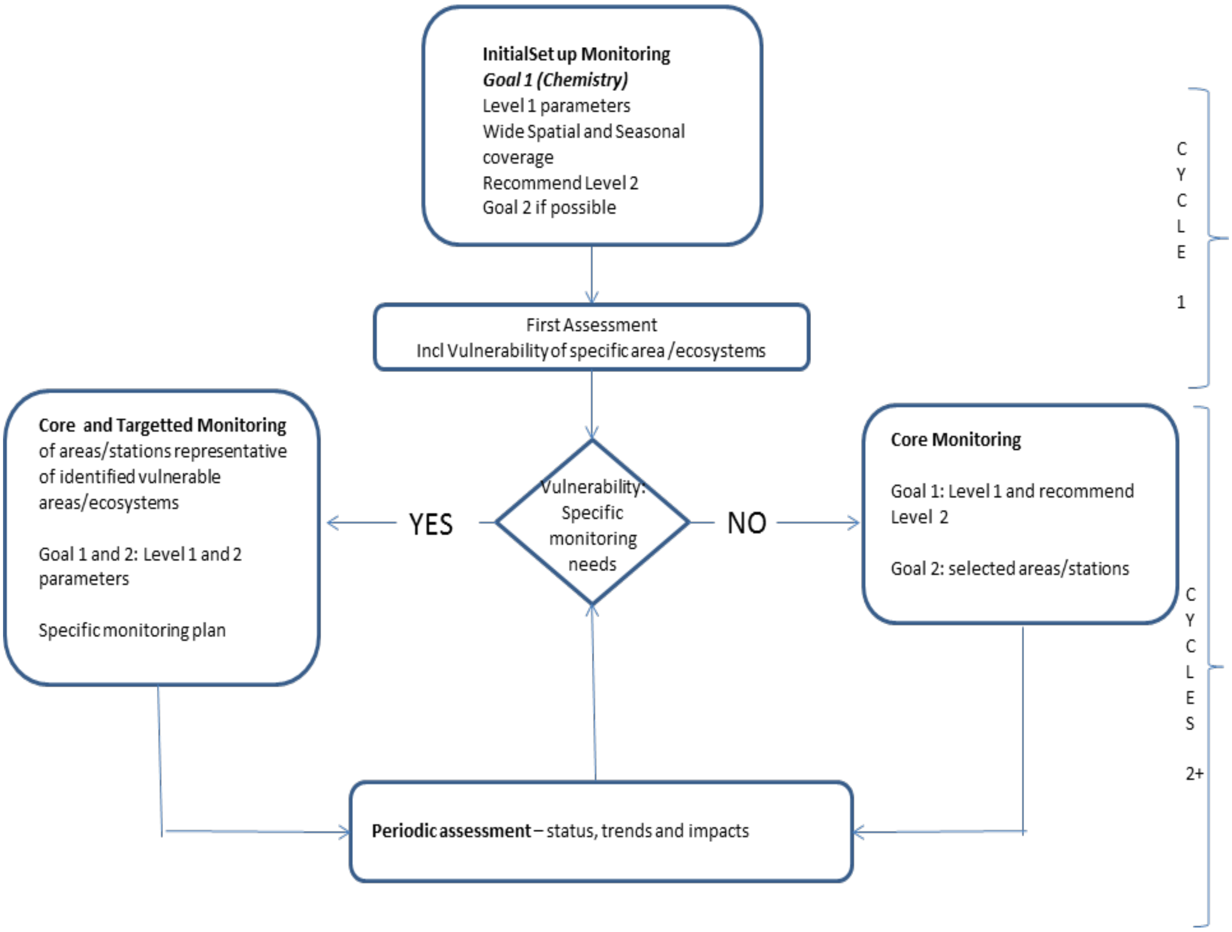


Figure 2. A conceptual diagram for an OSPAR monitoring strategy.

5. Data Quality Objectives and Quality Assurance

5.1 It is essential that data reported is fit for purpose and of a verifiable quality and consistency. GOA-ON recognise that different data quality objectives are required for different monitoring purposes which are represented as "Weather"vs. "Climate."

Table 3. Data Quality Levels for the Global OA Observing Network[11] (Source Newton *et al.*, 2014).

"CLIMATE"	"WEATHER"
• Defined as measurements of quality sufficient to assess long-term trends with a defined level of confidence • With respect to OA, this is to support detection of the long-term anthropogenically driven changes hydrographic conditions and carbon chemistry over multidecadal time-scales	• Defined as measurements of quality sufficient to identify relative spatial patterns and short-term variation • With respect to OA, this is to support mechanistic interpretation of the ecosystem response to, and impact on, local, immediate OA dynamics
climate objective requires ± 1% better measurement resolution of Ω. • This implies An uncertainty of approximately; 0.003 pH, 2 μmol kg^{-1} TA and DIC and a relative uncertainty of 0.5% in pCO$_2$ • Only achievable by a very limited number of laboratories. • Not typically achievable by the best autonomous sensors	weather objective requires ±10% measurement resolution of Ω. • This implies an uncertainty of approximately; 0.02 pH, 10 μmol kg^{-1} TA and DIC and relative uncertainty of 2.5% in pCO$_2$ • Achievable in competent laboratories. • Achievable with best autonomous sensors.

5.2 Quality Assurance requirements

5.2.1 Measurement uncertainty should be included data reporting.

5.2.2 Observations must be calibrated to a community-accepted set of reference materials and monitoring must be supported by frequent intercalibrations/proficiency testing.[12]

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[11] More information is available in Table 1 of OSPAR JAMP Guidelines for Monitoring Chemical Aspects of Ocean Acidification (OSPAR 2014b).

[12] Further effort is needed to support the development of appropriate reference materials and availability of routine proficiency testing to underpin monitoring.

6. Reporting and Assessment

6.1 Data reporting

6.1.1 OSPAR OA monitoring data and associated QC and metadata should be reported to the ICES Environmental Database using agreed formats (ERF 3.2 format for discrete sample data). (OSPAR 2014b). This database is not suited to collect continuous sensor data e.g. pCO_2. The ICES Oceanographic Database is at present unsuited to the collection of OSPAR OA monitoring data due to limitations in storing relevant QC/method metadata.

6.1.2 The ICES Environmental Database ERF3.2 format is able to accept biological effects data and should be adaptable to accept OA related biological effects monitoring data.

6.1.3 Relevant riverine input data should be reported to the OSPAR RID database.

6.1.4 It is not recommended that calculated carbonate parameters are reported. Should they be so they should be clearly flagged and all constants applied in the derivation of calculated parameters documented and reported?

6.1.5 It is further recommended that OSPAR ocean carbon and metadata are reported to the CDIAC international database which can accept carbon data including (semi-)continuous sensor data and appropriate metadata. Such data should be flagged in CDIAC database as OSPAR data.

6.1.6 OSPAR data should be collected and reported so as to be available to the global science community and suitable for inclusion in key OA-relevant global data-synthesis products, specifically SOCAT (surface pCO2 atlas) and GLODAP.

6.2 Assessment:

6.2.1 Periodic assessments [13]should be undertaken. Monitoring data may be used to construct assessment products for OSPAR area, regions and subregions. Indicators that can communicate the spatial extent, progression and threat of OA to a wide variety of stakeholders are required. Assessment products documenting status and trends of OA in the OSPAR area could include, but are not limited to: maps and graphical representations of long-term change in Ω/pH, maps and graphical representations of changes in spatial/seasonal extent of surface undersaturation, shoaling of saturation horizons, forecasts, and reviews of the status of biological metrics suitable for interpreting changes, etc. These require a baseline to be established against which to establish future change with the understanding that the baseline is likely to be moving. An assessment at the end of the first cycle should incorporate a vulnerability assessment of the OSPAR area and its subregions.

6.2.2 Assessment Criteria:

Chemical Assessment Criteria are not proposed at present and the [conceptual] approach to these for OA requires further consideration by OSPAR. Biological assessment criteria are still evolving. As appropriate techniques,

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[13] A ~six year interval is suggested tying in with MSFD and OSPAR Quality Status Report cycles.

metrics, and new indicator organisms are identified, these should be evaluated, and where appropriate, incorporated into the assessment.

7. References

AMAP. 2013. AMAP Assessment 2013: Arctic Ocean Acidification. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway. viii + 99 pp.

Cai, W.-J., Hu, X., Huang, W.-J., Murrell, M. C., Lehrter, J. C., Lohrenz, S. E., Chou, W.-C., *et al.* 2011. Acidification of subsurface coastal waters enhanced by eutrophication. Nature Geoscience, 4: 766–770.

Duarte, C. M., Hendriks, I. E., Moore, T. S., Olsen, Y. S., Steckbauer, A., Ramajo, L., Carstensen, J., *et al.* 2013. Is Ocean Acidification an Open-Ocean Syndrome? Understanding Anthropogenic Impacts on Seawater pH. Estuaries and Coasts, 36: 221–236.

Feely, R.A., Fabry, V.J., Dickson, A.J., Gattuso, J.-P., Bijma, J., Riebesell, U., Doney, S., Turley, C., Saino, T., Lee, K. and Bates, N.R. 2010. An International Observational Network for Ocean Acidification. In, Anthony, K., Kleypas, J. and *et al.* (Eds.) *Proceedings of OceanObs'09: Sustained Ocean Observations and Information for Society. OceanObs'09: Sustained Ocean Observations and Information for Society* Noordwijk, the Netherlands, European Space Agency. (ESA Special Publication WPP-306). (doi:10.5270/OceanObs09.cwp.29).

Hydes, D. J., McGovern, E., and Walsham, P. (Eds.) 2013. Chemical aspects of ocean acidification monitoring in the ICES marine area. ICES Cooperative Research Report No. 319: 78.

ICES. 2010 "Monitoring methodologies for ocean acidification" Section 1.5.5.2 Special request advice June 2010, ICEA Advice 2010, Book 1. International Council for the Exploration of the Sea, Copenhagen http://www.ices.dk/sites/pub/Publication%20Reports/Advice/2010/Special%20Requests/OSPAR%20Monitoring%20methodologies%20for%20ocean%20acidification.pdf.

IPCC. 2011. Workshop Report of the Intergovernmental Panel on Climate Change Workshop on Impacts of Ocean Acidification on Marine Biology and Ecosystems [C. B. Field, V. Barros, T. F. Stocker, D. Qin, K. J. Mach, G.-K. Plattner, M. D. Mastrandrea, M. Tignor and K. L. Ebi (Eds.)]. IPCC Working Group II Technical Support Unit, Carnegie Institution, Stanford, CA, USA 164 pp.

IWG-OA. 2014. Strategic Plan for Federal Research and Monitoring of Ocean Acidification. Interagency Working Group on Ocean Acidification. USA. http://www.whitehouse.gov/sites/default/files/microsites/ostp/NSTC/iwg-oa_strategic_plan_march_2014.pdf.

Lee, K., Tong, L. T., Millero, F. J., Sabine, C. L., Dickson, A. G., Goyet, C., Park, G.-H., *et al.* 2006. Global relationships of total alkalinity with salinity and temperature in surface waters of the world's oceans. Geophysical Research Letters, 33: L19605.

Newton, JA, Feely, RA, Jewett, EB, Gledhill D. 2014. Global Ocean Acidification Observing Network: Requirements and Governance Plan http://www.goa-on.org/docs/GOA-ON_Plan_final_Sept_2014.pdf.

Nondal, G., Bellerby, R. G. J., Olsen, A., Johannessen, T., and Olafsson, J. 2009. Optimal evaluation of the surface ocean CO_2 system in the northern North Atlantic using data from voluntary observing ships. Limnology and Oceanography: Methods, 7: 109–118.

OSPAR. 2010. Quality Status report 2010. OSPAR Commission, London. 176pp. http://qsr2010.ospar.org/en/index.html.

OSPAR. 2014a. OSPAR Joint Assessment and Monitoring Programme (JAMP) 2014–2021. Agreement 2014-02.

OSPAR. 2014b. JAMP Guidelines for Monitoring Chemical Aspects of Ocean Acidification. OSPAR Agreement 2014-03. OSPAR Commission, London. http://www.ospar.org/documents/dbase/decrecs/agreements/14-03e_jamp_oa_guidelines.doc.

Steinacher, M., Joos, F., Frölicher, T. L., Plattner, G.-K., and Doney, S. C. 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. Biogeosciences, 6: 515–533.

Williamson, P., and Turley, C. 2012. Ocean acidification in a geoengineering context. Philosophical Transactions of the Royal Society A: Mathematical, Physical and Engineering Sciences, 370: 4317–4342.

Abbreviations

TA:	Total Alkalinity
DIC:	Dissolved Inorganic Carbon
pCO_2:	partial pressure of carbon dioxide
Ω:	aragonite/calcite saturation states
T:	Temperature
S:	Salinity
DO:	Dissolved Oxygen
PO4:	Phosphate
SiO4:	Silicate
TOxN:	Total Oxidised Nitrogen (nitrate + nitrite)
DOM:	Dissolved Organic Matter
PIC:	Particulate inorganic carbon
POC:	Particulate organic carbon
$CaCO_3$	Calcium carbonate
CO_3^{2}	Carbonate ion
VOS:	Volunteer observing ships

AMAP	Arctic Monitoring and Assessment Programme
GOA-ON	Global Ocean Acidification Observation Network
CDIAC:	Carbon Dioxide Information Analysis Center
IPCC	International Panel on Climate Change
IOC	Intergovernmental Oceanographic Commission
OA	Ocean Acidification
SGOA	Joint OSPAR-ICES Study Group on Ocean Acidification
IWG-OA	Interagency Working Group on Ocean Acidification (US)

Annex 6: Ocean Acidification: an assessment of current and projected exposure of Cold Water Coral areas in the Northeast Atlantic

1. Cold-Water Corals in the OSPAR area

Cold-water corals (CWCs) are cnidarians encompassing stony corals (Scleractinia), soft corals (Octocorallia), black corals (Antipatharia) and hydrocorals (Stylasteridae) (Roberts *et al.*, 2006). Some of the scleractinians are key habitat engineers as they form reefs that are biodiversity hot spots. In the Northeast Atlantic *Lophelia pertusa* reefs are widespread along the shelf slopes and on flanks of seamounts at depths ranging from 200–2000 m, although they can occur in shallower water, for example in some Norwegian Fjords, where they have been found in water as shallow as 37 m (OSPAR 2009; Tittensor *et al.*, 2010; pers. comm. J. Järnegren). *Madrepora oculata* frequently co-occurs with *L. pertusa* as a secondary reef framework-former and *Solenosmilia variabilis* forms small reef patches on NE Atlantic Seamounts in deeper, colder water masses (Henry *et al.*, 2014). The reefs occur in hydrodynamically active environments where the supply of organic material is sufficiently abundant to support growth. Figure 1 shows the known distribution of *L. pertusa* reefs in the OSPAR area (http://www.emodnet-seabedhabitats.eu/default.aspx). *L. pertusa* spawns annually in January-March (Brooke and Järnegren, 2013). The larvae are likely planktotrophic and can survive up to two months in the water column before they settle on hard substrata (Larsson *et al.*, 2014). Temperature, aragonite saturation state and salinity are important factors in determining cold-water coral habitat suitability (Davies and Guinotte, 2011). Respective temperature and salinity boundaries are 4–13°C and 35–38 psu (OSPAR, 2009; Roberts *et al.*, 2006). Globally, cold-water scleractinian reefs occur above the depth of the Aragonite Saturation Horizon[14] (ASH; Guinotte *et al.*, 2006), and this factor helps explain the relative abundance in the NE Atlantic where the ASH is >2000 m, much deeper than in the North Pacific Ocean. The projected dramatic shoaling of the ASH over the next century is a threat to these reef structures (Orr *et al.*, 2005; Jackson *et al.*, 2014).

The biology and ecology of *L. pertusa* is described in Järnegren and Kutti (2014). A key feature of *L. pertusa* is its ability to develop extensive and complex reef structures subject to growth and bioerosion processes. Their gross morphology can be categorised according to whether it reflects the topography of the colonised features (inherited forms) or whether they assume their own gross morphology mainly reflecting hydrodynamic controls (developed forms) (Wheeler *et al.*, 2007).

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[14] The aragonite (calcium carbonate mineral in corals) saturation state (Ω_{AR}) is a function of pressure and seawater carbon chemistry. The Aragonite Saturation Horizon (ASH) is the depth at which $\Omega_{AR}=1$. Below the ASH seawater is undersaturated with respect to aragonite ($\Omega_{AR}<1$) and dissolution is favoured over precipitation, i.e. water is corrosive to aragonite.

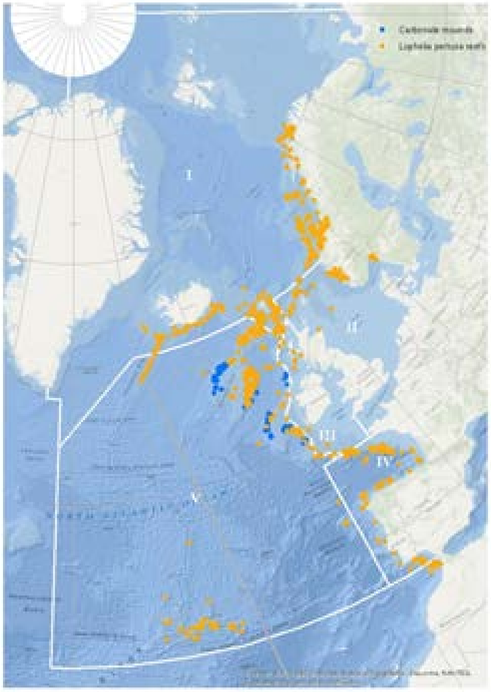


Figure 1. Distribution of *Lophelia pertusa* and carbonate mounds in the OSPAR area from OSPAR Threatened and Declining Habitats geodatabase. Data from MESH/EMODNET (May 2014).

2. Physical Oceanographic Control (Martin White)

Hydrographic control of cold-water coral functioning, via the linkage of physical processes with the delivery of organic material and nutrients to coral ecosystems, is now widely appreciated (e.g. Mohn *et al.*, 2014; Mienis *et al.*, 2007; White *et al.*, 2005; Davies *et al.*, 2008). These physical processes occur over a full spectrum of time and length scales (Figure 2), ranging from micro-scale turbulence up to basin-scale ocean structure determined by the Earth's energy budget and climatic processes.

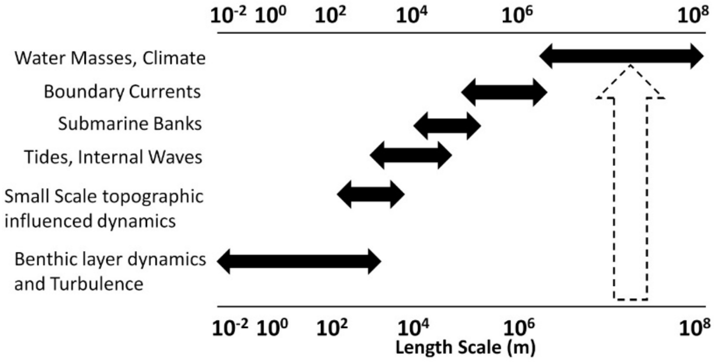


Figure 2. The length scales of the principal hydrographic processes that control cold-water coral ecosystem function. The vertical dashed arrow signifies the increasing influence of surface productivity (coupled with the dynamics) with length scale.

Hydrographical control occurs through a number of basic biophysical coupling mechanisms;

i) Large-scale atmospheric-ocean interactions that set basic ocean structure and properties which in turn define physical and chemical tolerances, e.g. temperature, salinity and ocean chemistry as well defining surface productivity magnitude;

ii) Physical processes that provide persistent conditions for appropriate sediment transport, i.e. that prevents depositional conditions but also promote suitable organic sediment fluxes to the environment;

iii) Smaller scale processes that locally enhance sediment fluxes through enhancement of sediment concentration or accelerated flow conditions.

The coupling of the surface productivity and the dynamics which then ‘delivers’ the organic material is major issue in the provision of energy to coral ecosystems. As Figure 2 indicates, the relative importance of processes that determine sufficient organic matter availability, relative to the dynamics advecting organic matter, increases with length scale. This is intuitive; at large scales the basic control is sufficient food to support the benthic communities, but at smaller scales different benthic faunal distributions will be determined by the dynamical processes that transport or concentrate the background organic matter supply.

At the largest scales, the basin scale oceanic forcing provides the basic environmental background tolerance conditions for cold-waters corals, e.g. temperature range (Freiwald, 2003), or the calcite compensation depth (CCD) and ASH (e.g. Orr *et al.*, 2005; Davies *et al.*, 2008). In addition, the large-scale physical forcing determines the degree of vertical overturning and cycling of nutrients that promote enhanced pelagic productivity e.g. the North Atlantic Current nutrient stream (Pelegri *et al.*, 1996).

At intermediate length scales, of order 100–1000 km, the interaction between topography, water column structure and physical forcing mechanisms play the most significant role in the cold-water coral ecosystem functioning. Within the subpolar realm where productivity levels are high, physical processes associated with the continental slope or submarine banks enhance the flux of organic material to the benthic ecosystems. Boundary currents can act as a persistent driver of downslope flow and variations in these boundary flows may result in regions where particle concentration is increased (e.g. Thiem *et al.*, 2006). The permanent thermocline, a ubiquitous feature in the ocean, can control the vertical depth range of carbonate mounds in the NE Atlantic through its role in generating strong residual and tidally periodic motions (White and Dorschel, 2010; Fossa *et al.*, 2005; Thiem *et al.*, 2006; Freiwald, 2002). Such enhanced currents occur where ‘resonances’ or hot spots of strong tidal baroclinic energy. Indeed, a feature of the carbonate mound province locations and the smaller submarine banks of the northern Rockall Trough, is the presence of strong tidally periodic motions, due to either internal waves (e.g. Mohn *et al.*, 2014; White, 2006) or bottom trapped diurnal period motions (White *et al.*, 2007; Mienis *et al.*, 2007). The length scales where resonance exist between the bottom topography and tidal forcing mechanisms likely determine the extent, both horizontally and vertically, of carbonate mound provinces (e.g. Mienis *et al.*, 2007).

At smaller length scales, (~1–10 km), similar current-topography interactions may occur that enhance particle fluxes to benthic ecosystems. Davies *et al.* (2009) have shown how tidally periodic hydraulic control processes can produce rapid downwelling of organic rich surface water to a shelf sea reef of limited horizontal extent, with concomitant implications on local carbonate chemistry (Findlay et al 2013). Genin *et al.* (1986) have shown how topographically induced current acceleration may determine the distribution of stony black corals on seamounts, with increased abundance near peaks and certain flanks where flow acceleration would be expected. For these two cases, the currents facilitate the concentration of particles and their advection across the ecosystem, thus increasing the flux of particles available to the corals. Dorschel *et al.* (2007) have shown the significant variability associated with the different topographic slopes and features of a single carbonate mound of diameter ~1 km. At yet smaller scales (cm-m) seabed induced turbulence will be modulated significantly by the reef composition itself, significantly impacting on the sediment mobility (e.g. Guihen *et al.*, 2013; Larsson and Purser, 2011), feeding/capture efficiency (e.g. Purser *et al.*, 2010) and the diffusion of gases or other chemical compounds associated with coral habitat functioning (e.g. Wild *et al.*, 2009). While there is a wealth of research in ecomechanics and eco-engineering for a number of benthic suspensions feeders and tropical coral counterparts, research on cold-water coral ecosystems is rather limited.

3. Ecological Function and Services

Many OSPAR Contracting Parties have put in place measures to protect CWC reef areas driven by recognition of how easily they are damaged. Our understanding of the ecological function and the ecosystem services provided by cold-water coral reefs is incomplete (Armstrong *et al.*, 2014). The reefs may function as nurseries, breeding and spawning areas for fish, (Baillon *et al.*, 2012) and provide habitat for many demersal fish, including commercial important species, providing protection from predators and foraging habitat (Järnegren *et al.*, 2014; Söffker *et al.*, 2011; Foley *et al.*, 2010). A service of CWCs ecosystems with very promising commercial possibilities relates to biodiscovery. The characteristics of organisms that survive in deeper environments offers the opportunity to discover new biochemical compounds and materials that may have industrial or pharmaceutical value (Armstrong *et al.*, 2014).

4. Ocean acidification and other anthropogenic stressors

Despite their inaccessibility, CWCs are threatened by multiple anthropogenic stressors with the damage from trawling gear an immediate concern which has led to protective measures being implemented for many CWC reefs (Järnegren *et al.*, 2014; Hall-Spencer *et al.*, 2009; Ramirez-Llodra *et al.*, 2011). In the longer term, however, ocean warming and ocean acidification (OA) are expected to become significant concerns (Jackson *et al.*, 2014). Ocean warming may have several effects that could impact on deep benthic communities, including increased stratification and reduced vertical mixing, reduced oxygenation of the ocean interior, and changes to circulation patterns (Ramirez-Llodra *et al.*, 2011).

There are currently several research groups working on the vulnerability of cold-water coral habitats to OA. Recent studies have indicated that *L. pertusa* calcification rates are not strongly affected at predicted CO_2 levels for this century (Form and Riebesell, 2012; Maier *et al.*, 2013) although one study observed reduced respiration (Hennige *et al.*, 2014). Although, there is little information on the effects of OA on recruitment of CWCs, research on tropical corals demonstrates that OA has the potential to affect sexual reproduction and early life stages of corals that are critical to reef persistence and resilience (Albright, 2011).

Many CWC species already live at depths well below the aragonite saturation horizon (Lunden *et al.*, 2013) and in shallow waters these species can form habitats exposed to aragonite undersaturation (Försterra and Häusserman, 2003). It appears that in the absence of other stressors, and if enough food is present, cold-water scleractinians can tolerate aragonite undersaturation (Rodolfo-Metalpa *et al.*, 2011, 2015). However, Flögel *et al.*, 2014) considered the physical and hydrochemical constraints on corals in the NE Atlantic and Mediterranean Sea and concluded that pristine reefs are limited to bottom waters with DIC values of <2170 µmol kg^{-1}, revealing a "tipping point" with respect to DIC.

Findlay *et al.* (2014) considered the fine scale dynamics at four North Atlantic sites that are known habitats for CWCs. At two sites fine scale hydrodynamics caused increased variability in the carbonate and nutrient conditions over daily time-scales so the *L. pertusa* present must be tolerant of widely fluctuating conditions. For instance, at the Logachev carbonate mound on the southern Rockall bank, they recorded a variation in aragonite saturation state at 600 m depth of ~0.2 over a 12 hour period. Future assessments of the threat from OA should take into account not only the fine scale variability but also consider the acidification rates of different water masses to which corals are exposed. Repeat hydrography (McGrath *et al.*, 2012) has indicated acidification of surface water and deeper waters (such as Labrador Sea Water) in the Rockall Trough over two decades.

While living polyps may be able to cope with the levels of CO_2 predicted for this century the unprotected dead coral skeleton that forms reefs is likely to start to dissolve as the aragonite saturation horizon (ASH) shoals (Tittensor *et al.*, 2010; Jackson *et al.*, 2014) and the reefs may be more vulnerable to bioerosion (Wisshak *et al.*, 2012). The alteration of habitat, due to loss of reef structure, could have serious implications for the corals and the associated ecosystem (Järnegren *et al.*, 2014). Guinotte *et al.* (2006) estimated that 70% of the known CWC ecosystems, most of which are in the North Atlantic, will be in water that is undersaturated with aragonite by 2099, resulting in weaker coral structures with slower growth rates. Orr *et al.* (2005) estimated that the ASH will shoal from 2600 m to 115 m in the Atlantic north of 50°N and Steinacher *et al.* (2009) estimate that surface waters of the Arctic will be undersaturated in aragonite within a decade. In the Iceland Sea the ASH is at 1710 m and shoaling at 4 m yr^{-1} (Olafsson *et al.*, 2009) resulting in an additional ~800 km^2 of seabed being exposed to undersaturated waters each year.

5. Current and projected future aragonite saturation states in the OSPAR area. (Are Olsen NO, Jerry Tjiputra NO)

5.1 Methodology

The seawater saturation degree of the calcium carbonate mineral aragonite, Ω_{Ar} is defined as the ratio between the product of its *in situ* constituent ion concentrations, calcium, $\mathbf{Ca^{2+}}$ and carbonate, $\mathbf{CO_3^{2-}}$, and their expected ion product when in equilibrium with the mineral phase, $\mathbf{K^*_{sp}}$:

$$\Omega_{Ar} = \frac{[Ca^{2+}][CO_3^{2-}]}{K^*_{sp}} \tag{1}$$

The concentration of calcium does not vary by much in the ocean and is primarily related to the seawater salinity. The concentration of carbonate is primarily determined by the concentrations of Dissolved Inorganic Carbon (DIC) and Alkalinity (ALK), and the solubility product (K_{sp}^*) is mostly pressure dependent (Sarmiento and Gruber, 2006). In addition, temperature, salinity and concentrations of phosphate (PO_4) and silicate (Si) have some effect on the saturation state.

Current and projected future aragonite saturation states in the OSPAR area were determined using two approaches, a data-based method that assumes insignificant change in ocean biology and circulation for this century, and a calibrated model-based approach that also takes into account climate induced changes in these processes. While the latter, Norwegian Earth System Model (NorESM), approach includes the a wider OSPAR area, the former, Transient Steady State, focuses on the Nordic Seas only, a consequence of the lack of required data from the remainder OSPAR area.

The Transient Steady State projections for the Nordic Seas are based on observed seawater chemistry and estimates of anthropogenic CO_2 (C_{ant}) presented by Olsen *et al.* (2010). These data are for 2002, and hereafter referred to as 'present conditions'. The C_{ant} estimates represent the rise in ocean CO_2 concentrations since preindustrial times due to its increased carbon uptake in response to the rise in atmospheric CO_2 levels following fossil-fuel burning, cement production and land use change emissions. Figure 3a and b show bottom-water concentrations of DIC and C_{ant} in the Nordic Seas based on the data presented by Olsen *et al.* (2010). Figure 3c shows what the C_{ant} would have been for these waters, if they had been fully equilibrated with the increased atmospheric CO_2. In most places this is much larger than the actual increase. The reason for this difference is the time it takes for C_{ant} to penetrate from the surface ocean, where it is absorbed, down to deeper layers presented here. In the Transient Steady State approach we take the ratios of the actual (Figure 3b) to the saturation change (Figure 3c) in C_{ant} and use them to determine the rise in ocean C_{ant} that will result from historical and projected changes in atmospheric CO_2 concentrations. In essence, in each grid point the ratio is used as a scaling factor that relates the atmospheric CO_2 rise to the ocean seabed DIC response. We next add these to the preindustrial concentrations (obtained by subtracting the C_{ant}, Figure 3b, from the observed DIC, Figure 3a) to get the historical and projected DIC concentrations. The underlying assumptions are that changes in DIC resulting from changing ocean biology and/or circulation are negligible compared to the C_{ant} increase, and that the transport-times for surface-to-deep C_{ant} transport remain constant with time, thus assuming a steady state ocean circulation. The mathematical framework for the approach is presented by Gammon *et al.* (1982); Tanhua *et al.* (2007) and Skogen *et al.* (2014).

With the projected future DIC concentrations in place, $\left[CO_3^{2-}\right]$ is calculated as:

$$\left[CO_3^{2-}\right]=f\left(DIC,ALK,T,S,P,PO_4,Si\right) \tag{2}$$

where *f* is the system of equations relating the inorganic carbon species, using the refitted (Dickson and Millero, 1987) carbonate equilibrium constants of Merhbach *et al.* (1973). Values for parameters other than DIC were set to those observed at the 2002 survey, in accordance with the assumption of negligible changes in biology and ocean circulation. Next, concentration of calcium was assumed proportional to salinity following Riley and Tongudai (1967), K_{sp}^* was determined following Mucci (1983) with the pressure correction of Millero (1979), and finally aragonite saturation states were determined using equation (1). All of these calculations were carried out using the CO2SYS software (Lewis and Wallace, 1998) as implemented in MatLab (van Heuven *et al.*, 2011).

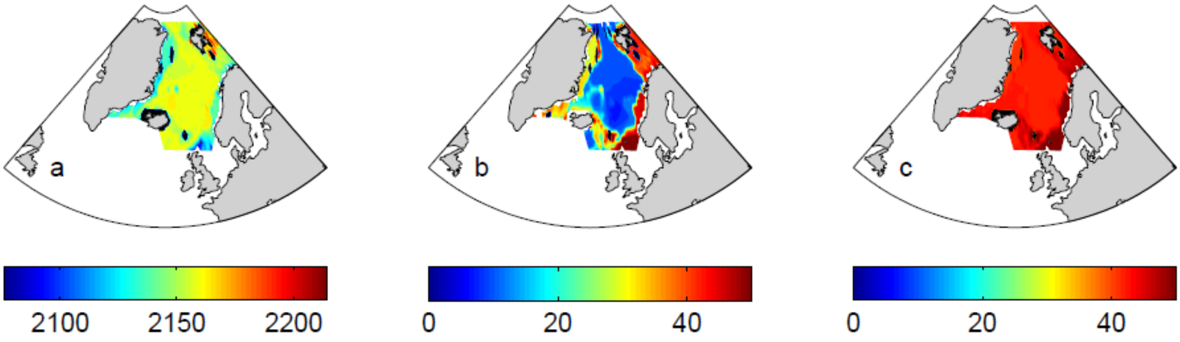


Figure 3. Nordic Seas near seabed concentrations of (a) DIC and (b) C_{ant} based on Olsen *et al.* (2010), and (c) theoretical C_{ant} in the case waters were fully equilibrated with the atmospheric CO_2 rise since preindustrial times.

The Norwegian Earth System Model (NorESM) projections were prepared using a global coupled climate-carbon model that projects the full climate system response to changes in greenhouse gas and other forcings. The NorESM (Bentsen *et al.*, 2013; Tjiputra *et al.*, 2013) consists of several components representing the ocean, atmosphere, sea ice, land biosphere, and ocean carbon cycle. Its projections were included in the model ensemble used in the latest assessment report, AR5, of the Intergovernmental Panel on Climate Change. Being a coupled global model, the NorESM is not ideally suited for regional assessments; as it is optimised with respect to large-scale performance regional bias may occur. To deal with this its alkalinity values were calibrated using the 2002 Nordic Seas data, so that the model's regional mean DIC/ALK ratio matches that of the observations. It is this ratio that has the strongest influence on the aragonite saturation values.

5.2 Results and Discussion

Figure 4 shows the observed Nordic Sea's bottom-water Ω_{Ar} values and transient steady state projected saturation states for 2100 for the four IPCC representative concentration pathways, RCP 2.6, RCP 4.5, RCP 6.0 and RCP 8.5. These four RCPs are named after their additional change in radiative forcing from pre-industrial times to 2100 of 2.6, 4.5, 6.0 and 8.5 W/m^2, respectively, and are associated with strong through to weak restrictions on CO_2 emissions. For RCP 2.6, the emissions peak between 2010 and 2020 and net negative emission occurs thereafter. For RCP 4.5 and 6.0 emissions peak around 2040 and 2080 and for the RCP8.5 emissions increase over the entire century.

Present Nordic Seas near seabed aragonite saturation state ranges from undersaturated (Ω_{Ar} <1) to oversaturated (Ω_{Ar} >1), and is closely tied to bottom depth. Deep in the basins of the Norwegian and Greenland Sea, concentrations of DIC are high due to accumulation of remineralised carbon over time. This drives the aragonite saturation state down. Over the shelf areas on the other hand, waters are better ventilated and contain less DIC, hence these have higher aragonite saturation state. All of the shelf areas where the cold-water coral *L. pertusa* exists are currently supersaturated. In all four transient steady state projections of 2100 conditions, aragonite saturation states are lower. For the RCP2.6 scenario, the changes are subtle, and the position of the $\Omega_{Ar} = 1$ isoline is more or less equal to its present. This is not surprising as the atmospheric CO_2 concentration for the year 2100 in this scenario is not more than 421 ppm, which is only 49 ppm greater than the concentration in 2002. For RCPs 4.5 and 6.0, the 2100 atmospheric CO_2 is 538 and 670 ppm, respectively, and the degree of aragonite saturation is clearly lower for these projections. The most vulnerable locations under the most pessimistic of these two intermediate scenarios are the Røst reef off the Lofoten Islands and the reefs at the northern edge of the Faroe-Iceland Ridge, where Ω_{Ar} will be close to 1 by the year 2100. In the RCP8.5 scenario, atmospheric CO_2 concentration reaches 936 ppm by 2100. This is about twice that of present, and according to our projection here, this will generate undersaturated conditions at essentially all known Nordic Sea locations of *L. pertusa* reefs as plotted on the maps.

The projected near seabed aragonite saturation states projected with the NorESM is displayed in Figure 5. These include the entire OSPAR area, and show that for 2002, most but not all *L. pertusa* reefs are found in supersaturated waters; the reef at the western edge of the Porcupine Bank and two locations just to the east of the Amorican margin apparently occur in waters at saturation level. Note that, however, since the model output has been calibrated with Nordic Sea data only, these values may be slightly off and measurements in this region suggest the ASH to be at a depth of >2000 m (McGrath *et al.,* 2012). For the future scenarios the model runs indicate Nordic Sea ocean acidification more or less similar to the transient steady state projections shown in Figure 4. In the North Atlantic the model projections indicate that under RCP4.5 water surrounding all reefs at the Reykjanes Ridge and many of the reefs at the southern Iceland shelf will be at close to $\Omega_{Ar} = 1$ in 2100. The same applies for the edge of the Hatton and Porcupine Banks. Under the RCP6.0 scenario, many of these shelf edge locations will be exposed to corrosive waters. Under the RCP8.5 scenario most North Atlantic reefs will experience corrosive conditions by the year 2100. The exceptions are the reefs at the Celtic and Amorican margins. The waters surrounding the shallowest of these will still be above saturation in 2100, even under the RCP8.5 projection, according to the NorESM projections.

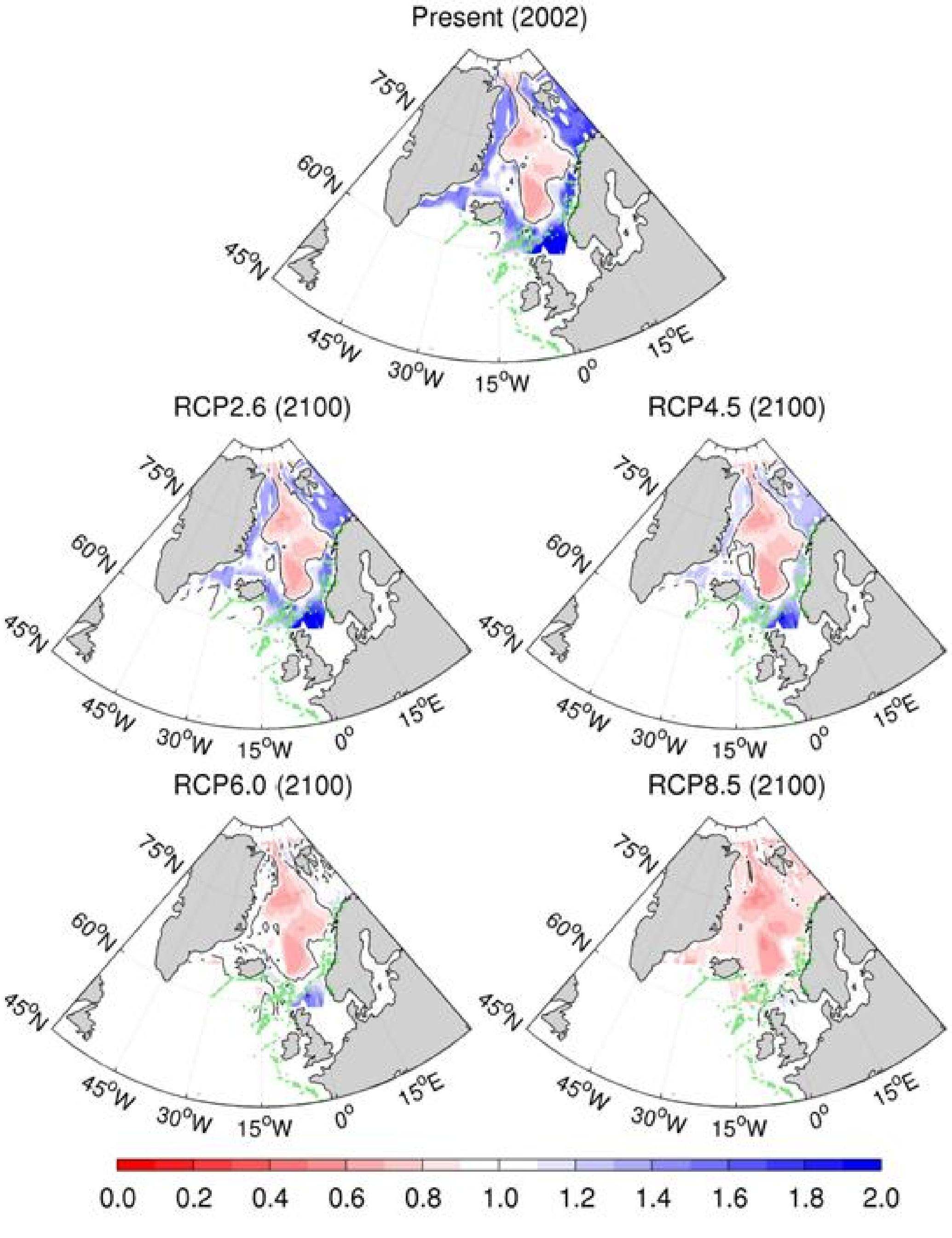
In Figures 6 and 7, we present time-series of aragonite saturation states at the locations of the Røst and Storegga reefs, determined using both the transient steady state approach and the NorESM. These time-series include also the hindcasts for past atmospheric CO_2 values, and show how the aragonite saturation state have dropped since preindustrial times, from about 2.1 to 1.7 at the Røst reef and from about 2.2 to 1.7 at the Storegga reef. Both projections indicate that the reefs will be exposed to undersaturated waters under RCP8.5, but not under the other scenarios. For both locations, undersaturated conditions are projected to occur at around 2080–2090.

To consider how Marine Protected Area networks might be designed to consider against future changes as well as current pressures, Jackson *et al.* (2014) considered both fishing pressure and projections for aragonite saturation states for known and predicted CWC reef habitat in Irish and UK EEZ. The projections were based on IS92a “business as usual” and IPCC SRES emission scenarios. The projections show that in the best case scenario (SRES B1) undersaturated waters do not impact on the reefs by 2099 but in the worst case (“business as usual”) scenario over 85% of the reefs would be exposed to corrosive water ($\Omega_{Ar}<1$) by 2060. Modelling the other scenarios also showed much of the reef habitat exposed to corrosive waters by the end of the century.

6. Conclusions

This assessment indicates that if we do not curb CO_2 emissions much of the cold-water coral reef habitat in the OSPAR area will be exposed to corrosive waters by the end of the century. This is likely to lead to irreversible damage and loss of reef habitat, to the detriment of the important ecological function and services provided by these ecosystems. The assessments are based on coarse models of saturation state but it is clear that CWC ecosystems are exposed to spatial and temporal hydrodynamic variability on a variety of scales. Such fine-scale dynamics are not addressed in such models. Research monitoring and enhanced modelling capabilities are needed to better understand the current conditions to which CWCs are exposed; to predict the impact of current and future OA conditions on living corals and on habitat structure; and to improve predictions as to how multiple stresses will impact on reef ecology and ecosystem services.

Contributors to this assessment were Are Olsen (NO), Jerry Tjiputra (NO), Evin McGovern (IE), Martin White (IE), Jason Hall-Spencer (UK), Melissa Chierici (NO), Johanna Järnegren (NO) and Murray Roberts (UK).


Present (2002)

RCP2.6 (2100)

RCP4.5 (2100)

RCP6.0 (2100)

RCP8.5 (2100)

Figure 4. Nordic Seas near-seabed aragonite saturation states observed in 2002 and projected for 2100 using the Transient Steady State approach under four different Representative Concentration Pathways. The black isolines represent saturation state of one, and the green markers represent locations of reef habitats extracted from the 2013 OSPAR priority habitats map published through EMODnet.

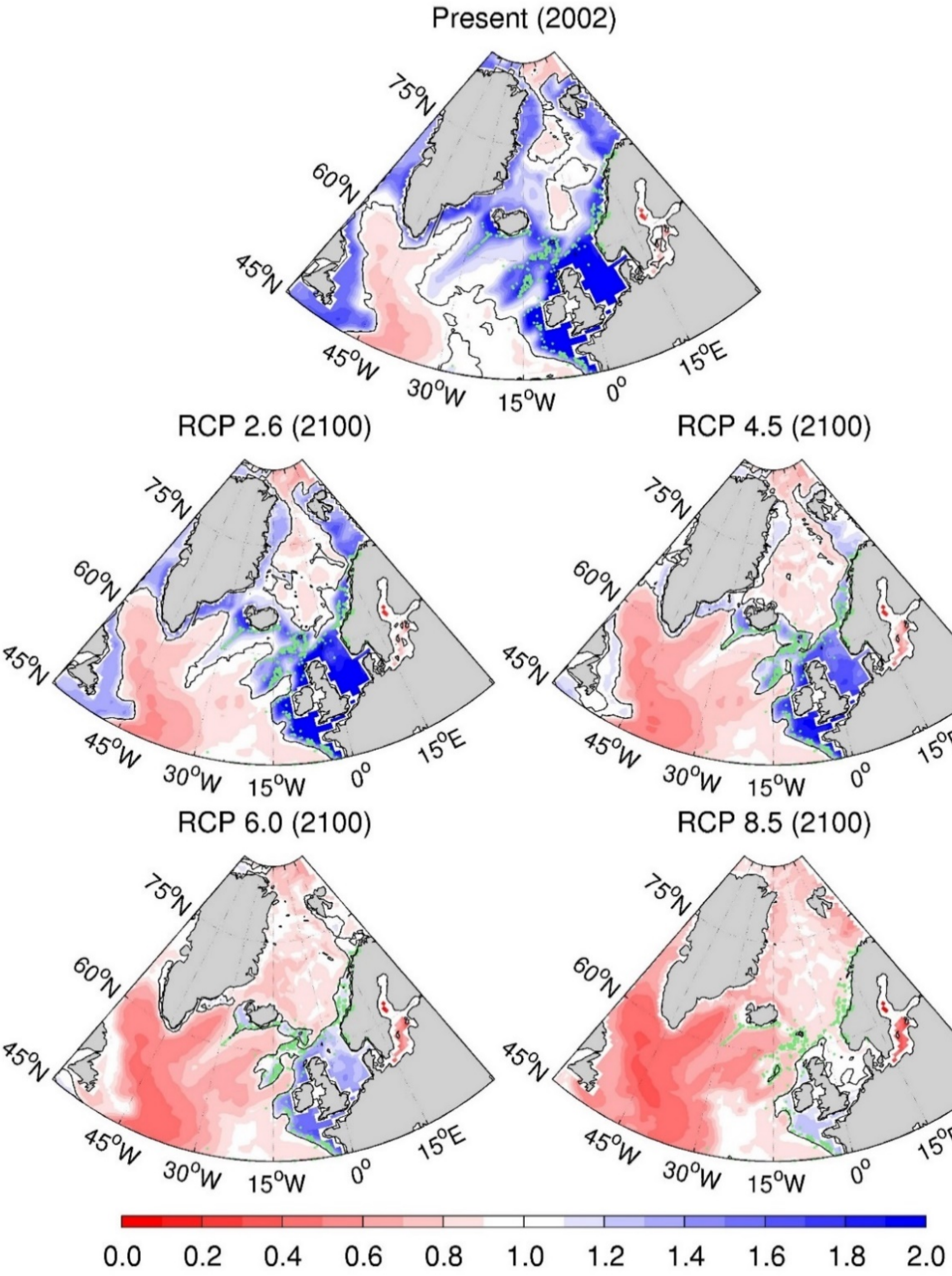


Figure 5. Similar to Figure 4 for the whole OSPAR area as simulated by data-calibrated NorESM.

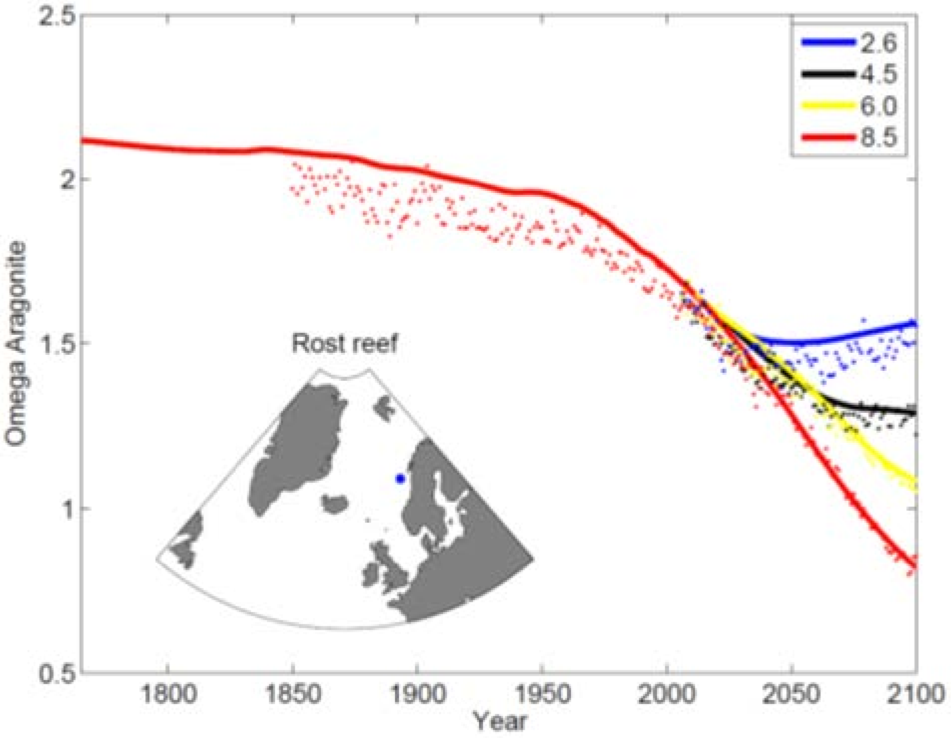


Figure 6. Time-series of historical and future aragonite saturation at the Røst reef determined using the transient steady state approach (solid lines) and the calibrated NorESM (dots) for the four IPCC Representative Concentration Pathways.

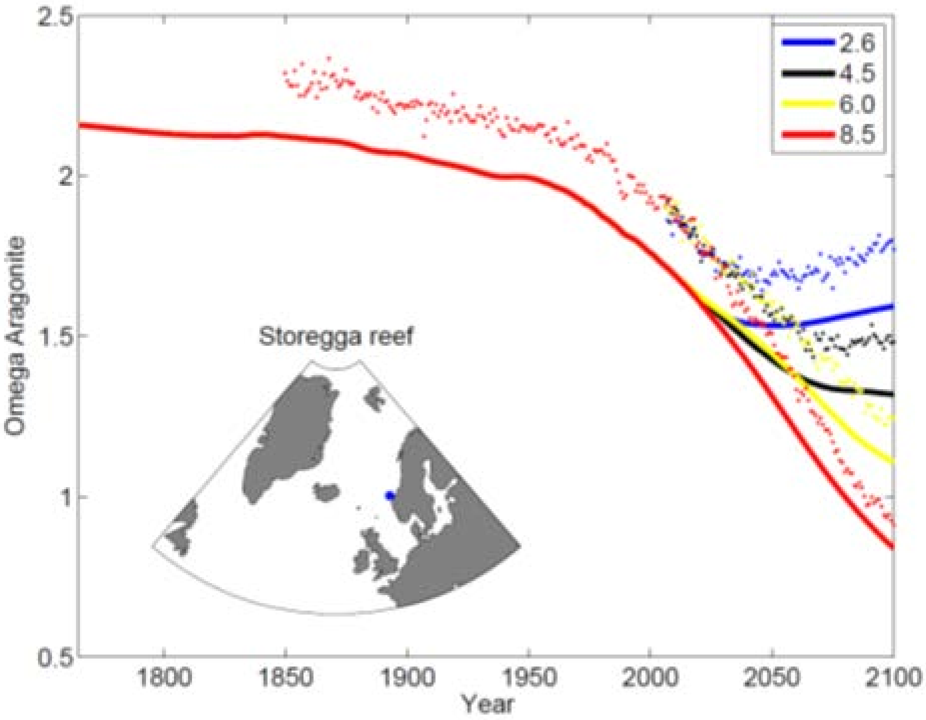


Figure 7. Time-series of historical and future aragonite saturation at the Storegga reef determined using the transient steady state approach (solid lines) and the calibrated NorESM (dots) for the four IPCC Representative Concentration Pathways.

7. References

Armstrong, C. W., Foley, N. S., Kahui, V., and Grehan, A. 2014. Cold water coral reef management from an ecosystem service perspective. Marine Policy, 50, Part A: 126–134.

Albright, R. 2011. Reviewing the Effects of Ocean Acidification on Sexual Reproduction and Early Life History Stages of Reef-Building Corals. Journal of Marine Biology, 2011: e473615.

Baillon, S., Hamel, J.-F., Wareham, V. E., and Mercier, A. 2012. Deep cold-water corals as nurseries for fish larvae. Frontiers in Ecology and the Environment, 10: 351–356.

Bentsen, M., Bethke, I., Debernard, J. B., Iversen, T., Kirkevåg, A., Seland, Ø., Drange, H., *et al.* 2013. The Norwegian Earth System Model, NorESM1-M - Part 1: Description and basic evaluation of the physical climate, Geosci. Mod. Dev., 6: 687–720.

Brooke, S. and Järnegren J. 2013. Reproductive periodicity of the scleractinian coral, *Lophelia pertusa* from the Trondheim Fjord, Norway. Marine Biology, 160: 139–153.

Davies, A, Wisshak, M., Orr, J.C., and J.M. Roberts. 2008. Predicting suitable habitat for the cold-water coral *Lophelia pertusa* (Scleractinia). Deep Sea Res., 55: 1048–1062. http://www.sciencedirect.com/science/article/pii/S0967063708000836.

Davies AJ, Duineveld GCA, Lavaleye MSS, Bergman MJN, Van Haren H, and Roberts, J. 2009. Downwelling and deep-water bottom currents as food supply mechanisms to the cold-water coral *Lophelia pertusa* (Scleractinia) at the Mingulay Reef Complex. Limnology and Oceanography 54: 620–629.

Davies, A.J. and Guinotte, J.M. 2011. Global Habitat Suitability for Framework-Forming Cold-Water Corals. PLoS ONE, 6: e18483.

Dickson, A. G. and F. J. Millero. 1987. A comparison of the equilibrium constants for the dissociation of carbonic acid in seawater media, Deep-Sea Res., 34: 1733–1743.

Dorschel B., Hebbeln D., Foubert A., White M., Wheeler A.J. 2007. Cold-water coral carbonate mound hydrodynamics and facies distributions: instrumentation and model development. Marine Geology, 244(1-4): 184–195.

Findlay, H. S., Hennige, S. J., Wicks, L. C., Navas, J. M., Woodward, E. M. S., and Roberts, J. M. 2014. Fine-scale nutrient and carbonate system dynamics around cold-water coral reefs in the Northeast Atlantic. Scientific Reports, 4. http://www.nature.com/srep/2014/140120/srep03671/full/srep03671.html (Accessed 11 December 2014).

Findlay, H.S., Wicks, L., Moreno Navas, J., Hennige, S., Huvenne, V., Woodward, E.M.S., Roberts, J.M. 2013. Tidal downwelling and implications for the carbon biogeochemistry of cold-water corals in relation to future ocean acidification and warming. Global Change Biology 19: 2708–2719.

Flögel, S., Dullo, W.-C., Pfannkuche, O., Kiriakoulakis, K., and Rüggeberg, A. 2014. Geochemical and physical constraints for the occurrence of living cold-water corals. Deep Sea Research Part II: Topical Studies in Oceanography, 99: 19–26.

Foley, N. S., Kahui, V., Armstrong, C. W., and Van Rensburg, T. M. 2010. Estimating Linkages between Redfish and Cold Water Coral on the Norwegian Coast. Marine Resource Economics, 25: 105–120.

Form, A. U., and Riebesell, U. 2012. Acclimation to ocean acidification during long-term CO_2 exposure in the cold-water coral *Lophelia pertusa*. Global Change Biology, 18: 843–853.

Försterra G, and Häusserman, V. 2003. First report on large scleractinian (Cnidaria: Anthozoa) accumulations in cold-temperate shallow water of south Chilean fjord. Zoologische verhandelingen Leiden, 345, 117–128.

Fossa, J-H., Lindberg, B., Christensen, O., Lundalv, T., Svellingen, I., Moretensen, P.B., and Alvsvag, J. 2005. Mapping of *Lophelia* reefs in Norway: experiences and survey methods.

In: Cold-water corals and ecosystems, Springer-Verlag, Berlin-Heidelberg, Freiwald A, Roberts, JM (eds.). 359–391.

Freiwald A. 2003. Reef-forming cold-water corals. In Ocean Margin Systems, Springer Berlin Heidelberg, 365–385.

Freiwald, A. 2002. The Sula Reef Complex, Norwegian Shelf. Facies, 47, 179–200.

Gammon, R. H., Cline, J, and Wisegarver, D. 1982. Chlorofluoromethanes in the Northeast Pacific Ocean: Measured vertical distributions and application as transient tracers of upper ocean mixing, J. Geophys. Res., 87: 9441–9494.

Genin, A., Dayton, P. K., Lonsdale, P. F. and Speiss, F. N. 1986. Corals on seamount peaks provide evidence of current acceleration over deep-sea topography. Nature, 322: 59–61.

Guihen, D., White, M., and Lundalv, T. 2013. Flow dynamics and turbulence generation at a cold-water coral reef. J. Sea Research, 78, 36–44.

Guinotte, J.M., Orr, J., Cairns, S., Freiwald, A., Morgan, L. and George, R. 2006. Will human-induced chemistry alter the distribution of deep-sea scleractinian corals? Frontiers Ecol. Environ. 4: 141–146.

Hall-Spencer, J.M., Tasker, M., Soffker, M., Christiansen, S., Rogers, S., Campbell, M., Hoydal, K. 2009. The design of Marine Protected Areas on High Seas and territorial waters of Rockall. *Marine Ecology Progress Series* 397: 305-308.

Hennige, S. J., Wicks, L. C., Kamenos, N. A., Bakker, D. C. E., Findlay, H. S., Dumousseaud, C., and Roberts, J. M. 2014. Short-term metabolic and growth responses of the cold-water coral *Lophelia pertusa* to ocean acidification. Deep Sea Research Part II: Topical Studies in Oceanography, 99: 27–35.

Henry L.-A., Vad, J., Findlay, H.S., Murillo, J., Milligan, R. and Roberts, J.M. 2014. Environmental variability and biodiversity of megabenthos on the Hebrides Terrace Seamount (Northeast Atlantic). Nature Scientific Reports 4: 5589.

Jackson, E. L., Davies, A. J., Howell, K. L., Kershaw, P. J., and Hall-Spencer, J. M. 2014. Future-proofing marine protected area networks for cold water coral reefs. ICES Journal of Marine Science: Journal du Conseil: fsu099.

Järnegren, J. and Kutti, T. 2014. *Lophelia pertusa* in Norwegian waters. What have we learned since 2008? - NINA Report 1028. 40 pp.

Larsson A.I., and Purser, A. 2011. Sedimentation on the cold-water coral *Lophelia pertusa*: Cleaning efficiency from natural sediments and drill cuttings. Mar. Poll. Bull., 62: 1159–1168.

Larsson A. I, Järnegren, J, Strömberg, S. M, Dahl, M. P, Lundälv, T, and Brooke, S. 2014. Embryogenesis and larval biology of the cold-water coral *Lophelia pertusa*. PLoS One, 9(7): e102222.

Lewis, E. and Wallace, D. 1998. *Program developed for* CO_2 *system calculations*, Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, USA.

Lunden, J.J., Georgian, S.E., Cordes, E.E. 2013. Aragonite saturation states of cold-water coral reefs structured by *Lophelia pertusa* in the northern Gulf of Mexico. Limnology and Oceanography, 58, 354–362.

Maier, C., Schubert, A., Berzunza Sànchez, M. M., Weinbauer, M. G., Watremez, P., and Gattuso, J.-P. 2013. End of the Century pCO_2 Levels Do Not Impact Calcification in Mediterranean Cold-Water Corals. PLoS ONE, 8: e62655.

McGrath, T., Kivimäe, C., Tanhua, T., Cave, R. R., and 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.

Merhbach, C. C., Culberson, H., Hawley, J. E. and Pytkowicz, R. M. 1973. Measurement of the apparent dissociation constants of carbonic acid in seawater at atmospheric pressure, Limnol. Oceanogr. *18*, 897–907.

Mienis, F., H.C. de Stigter, M. White, G. Duineveld, H. de Haas and T.C.E. van Weering. 2007. Hydrodynamic controls on cold-water coral growth and carbonate-mound development at the SW and SE Rockall Trough Margin, NE Atlantic Ocean. *Deep Sea Research*, 54(9), 1655–1674.

Millero, F. J. 1979. The thermodynamics of the carbonate system in seawater, *Geochim. Cosmochim. Ac.*, *43*, 1651–1661.

Mohn, C., A. Rengstorf, M White, G. Duineveld, F. Mienis, K. Soetaert, and A. Grehan. 2014. Linking benthic hydrodynamics and cold-water coral occurrences: A high-resolution model study at three cold-water coral provinces in the NE Atlantic. *Prog. Oceanogr*. 122, 92–104

Mucci, A. 1983. The solubility of calcite and aragonite in seawater at various salinities, temperatures and one atmosphere total pressure, *Am. J. Sci.*, *283*, 781–799.

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

Olsen, A., A. M. Omar, E. Jeansson, L. G. Anderson and R. G. J. Bellerby. 2010. Nordic seas transit time distributions and anthropogenic CO_2, *J. Geophys. Res.*, *115*, C05005, doi: 10.1029/2009JC005488.

Orr, J.C., Fabry, V.J., Aumont, O., Bopp, L., Doney, S.C., Feely, R.A. and Yool, A. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature* 437, 681–686.

OSPAR. 2009. Background Document for *Lophelia pertusa* reefs. Biodiversity Series Publication Number: 423/2009. Pp 31 OSPAR Commission, London.

Pelegri, J.L., Cassandy, G.T. and Martins, A. 1996. The North Atlantic nutrient stream. *J. Oceanography*, 52, 275–299.

Purser, A., Larsson, A.I., Thomsen, L., and van Oevelen, D. 2010. The influence of flow velocity and food concentration on *Lophelia pertusa* (Scleractinia) zooplankton capture rates. *J. Expt. Mar. Biol. And Ecology*, 395, 55–62.

Ramirez-Llodra, E., Tyler, P. A., Baker, M. C., Bergstad, O. A., Clark, M. R., Escobar, E., Levin, L. A., *et al*. 2011. Man and the Last Great Wilderness: Human Impact on the Deep Sea. *PLoS ONE*, 6: e22588.

Riley, J. P. and M. Tongudai. 1967. The major cation/chlorinity ratios in seawater, *Chem. Geol.*, *2*, 263–269.

Roberts, J.M., Wheeler, A.J. and Freiwald, A. 2006. Reefs of the Deep: The Biology and Geology of Cold-Water Coral Ecosystems. *Science* 312, 543–547.

Rodolfo-Metalpa, R., Houlbreque, F., Tambutte, E., Boisson, F., Baggini, C., Patti F.P., Jeffree, R., Fine, M., Foggo, A., Gattuso, J.-P., Hall-Spencer, J.M. 2011. Coral and mollusc resistance to ocean acidification adversely affected by warming, Nature Climate Change, 1(6): 308–312, doi: 10.1038/nclimate1200.

Rodolfo-Metalpa, R., Montagna, P., Aliani, S., Borghini, M., Canese, S., Hall-Spencer, J. M., Foggo, A., *et al.* 2015. Calcification is not the Achilles' heel of cold-water corals in an acidifying ocean. Global Change Biology: DOI: 10.1111/gcb.12867.Sarmiento, J. L. and N. Gruber 2006. *Ocean biogeochemical dynamics*, Princeton, University Press, Princeton, NJ, USA.

Skogen, M, A. Olsen, K. Y. Børsheim, A. B. Sandø and I. Skjelvan. 2014. Modelling ocean acidification in the Nordic and Barents Seas in present and future climate, *J. Mar. Sys.*, *131*, 10–20.

Söffker M, Sloman KA, Hall-Spencer JM. 2011. *In situ* observations of fish associated with coral reefs off Ireland. *Deep-Sea Research*, 58, 818–825.

Steinacher, M., Joos, F., Frölicher, T. L., Plattner, G.-K., and Doney, S. C. 2009. Imminent ocean acidification in the Arctic projected with the NCAR global coupled carbon cycle-climate model. *Biogeosciences*, 6: 515–533.

Tanhua, T., A. Körtzinger, K. Friis, D. W. Waugh, and D. W. R. Wallace. 2007. An estimate of anthropogenic CO_2 inventory from decadal changes in oceanic carbon content, *Proc. Natl. Acad. Sci. USA.*, *104*, 3037–3042.

Thiem O, Ravagnam, E, Fossa, J-H, and Berntsen, J. 2006. Food supply mechanisms for cold-water corals along a continental shelf edge. *J. Marine Systems*, 60, 207–219.

Tittensor, D. P., Baco, A. R., Hall-Spencer, J. M., Orr, J. C., and Rogers, A. D. 2010. Seamounts as refugia from ocean acidification for cold-water stony corals. *Marine Ecology*, 31: 212–225.

Tjiputra, J. F., C. Roedlandt, M. Bentsen, D. M. Lawrence, T. Lorentzen, J. Schwinger, Ø. Seland and C. Heinze. 2013. Evaluation of the carbon cycle components in the Norwegian Earth System Model (NorESM), *Geosci. Mod. Dev.*, *6*, 301–325.

van Heuven, S., D. Pierrot, J, W. B. Rae, E. Lewis, and D. W. R. Wallace. 2011. *CO2SYS Program Developed for CO_2 System Calculations in MATLAB,* Carbon Dioxide Information Analysis Center, Oak Ridge National Laboratory, Oak Ridge, TN, USA.

Wheeler, A. J., Beyer, A., Freiwald, A., Haas, H. de, Huvenne, V. a. I., Kozachenko, M., Roy, K. O.-L., *et al*. 2007. Morphology and environment of cold-water coral carbonate mounds on the NW European margin. International Journal of Earth Sciences, 96: 37–56.

White, M., C. Mohn, H. de Stigter and G. Mottram. 2005. Deep water coral development as a function of hydrodynamics and surface productivity around the submarine banks of the Rockall Trough, NE Atlantic. In: Cold-water corals and Ecosystems, Freiwald, Roberts (Eds.), Springer, 503–514.

White, M. 2006. Benthic Dynamics at the carbonate mound regions of the Porcupine Sea Bight continental margin. *International Journal of Earth Sciences*, 96, 1–9.

White, M., J Murray Roberts, and T. van Weering. 2007. Do bottom intensified diurnal tidal currents shape the alignment of carbonate mounds in the NE Atlantic? Geo-Marine Letters, dx.doi.org/10.1007/s00367-007-0060-8.

White, M, and Dorschel, B. 2010. The importance of the permanent thermocline to the cold water coral carbonate mound distribution in the NE Atlantic. *Earth Plan. Sci. Lett.*, 296, 393–402.

Wild C, Wehrmann LM, Mayr C, Schottner SI, Allers E, Lundalv T. 2009. Microbial degradation of cold-water coral derived organic matter: potential implication for organic C cycling in the water column above Tisler Reef. *Aquat. Biol.*, 7, 71−80.

Wisshak, M., Schönberg, C. H. L., Form, A., and Freiwald, A. 2012. Ocean Acidification Accelerates Reef Bioerosion. *PLoS ONE*, 7: e45124.

Annex 7: Long-term ocean acidification trends in the OSPAR area

Long-term changes in OA parameters are difficult to accurately quantify due to the limited data coverage, spatial heterogeneity of water masses and large seasonal, interannual and even decadal variability in the carbonate system (Feely *et al.*, 2009; Doney *et al.*, 2009; Friedrich *et al.*, 2012). Both short and long-term (multidecadal) changes in OA parameters are poorly documented and the challenge is therefore to measure the carbonate system with the precision and accuracy required to assess the trends that are due to ocean acidification. It is also important to distinguish between natural and anthropogenic changes in the carbonate system over time. In the North Atlantic, most of the air-sea uptake of anthropogenic CO_2 occurs in the subtropical gyre, whereas the Subpolar Gyre predominantly uptakes natural CO_2, where a reduction in the North Atlantic Oscillation coincides with a decrease in anthropogenic carbon storage in the subpolar region (Perez *et al.*, 2013; Perez *et al.*, 2008). In the OSPAR regions, where significant seasonal and interannual changes in pCO_2 and pH are observed, sustained monitoring on multiyear to decadal time-scales is required to discern the long-term trend (Hydes *et al.*, 2013; Tanhua *et al.*, 2013).

The Marine Chemistry Working Group (MCWG) has previously provided estimates of the spatial and daily, seasonal and interannual variability of carbonate system parameters in the OSPAR regions as well as long-term changes (Borges in Hydes *et al.*, 2013). SGOA reviewed available literature on long-term trends in ocean acidification for the North Atlantic and this information is presented in Table 1 for surface waters and Table 2 for deeper waters. Broadly four approaches are used for estimating long-term trends from available data:

- Long-term high frequency time-series stations (monthly or seasonal sampling) of carbonate system parameters at fixed stations;
- Annually reoccupied transects and sites;
- Infrequent/irregular reoccupation of previous transects (e.g. hydrographic surveys resampling of WOCE transects from 1990s);
- Trend assessments based on broadscale data syntheses. Typically this involves synthesis of surface ocean pCO_2 and estimating TA from the salinity to calculate OA parameters.

The only long-term time-series specifically for carbonate system parameters in OSPAR waters are the ~30 year series in the Icelandic Sea and Irminger Sea. However, other key North Atlantic time-series from outside the OSPAR area are also included, namely the Bermuda Atlantic Time-Series (BATs) and the European Station for Time-Series in the Ocean, Canary Islands (ESTOC).

The average annual rate of increase of atmospheric CO_2 over the past three decades was 1.78 ppm (1.40 ppm increase between 1984–1993; 1.87 ppm increase between 1993–2003; 2.07 ppm increase between 2003–2013) (Canadell *et al.*, 2007; LeQuere *et al.*, 2014). The reported rates of increase in pCO_2 in surface waters in most OSPAR regions are equivalent to or higher than the rate of increase in atmospheric CO_2 (Table 1). The reason for this is not always known but may be due to changes in circulation, e.g. vertical mixing (Corbière *et al.*, 2007) or horizontal distribution of water masses (Thomas *et al.*, 2008), or to the decrease in buffering capacity of seawater (Thomas *et al.*, 2007).

It is difficult to compare the reported trends in OA parameters due to several factors. The data were not necessarily obtained during the same seasons, the parameters were sampled at different temporal intervals (where sampling at fewer points in time increase the uncertainty related to interannual variability) and different parameters and calculation methods were used to determine the rates of change. For example, Olafsson *et al.*, 2009 reported a higher value for the pCO_2 trend in the Iceland Sea by using only the winter measurements from the dataset, relative to the pCO_2 trend reported in Bates *et al.* (2014) who used data from the whole year which was then seasonally detrended. To compare seawater CO_2-carbonate seawater trends at the world's main ocean time-series sites. Bates *et al.* (2014), used this same method to remove seasonality on all the datasets in their study, something that might not be suitable for the higher latitude waters where the spring bloom might not occur at the same time each year.

Overall while the there is a range of trends reported for surface waters in Table 1, all datasets indicate acidification, generally in the order of ~0.02 pH units per decade.

Table 2 presents information on estimated long-term ocean acidification in deeper water masses, although there are much fewer data available. These assessments are based on high quality carbonate system data collected on various hydrographic surveys in the North Atlantic over three decades. Again downward pH trends are evident albeit at a slower rate than reported for surface waters, as would be expected due to the lag time for surface CO_2 to penetrate the deeper ocean. Nevertheless, higher rates of acidification and reduction in aragonite saturation may occur in subsurface water masses relative to surface waters in some regions due to ventilation, biological processes and geochemical properties (Bates, 2012; Resplandy *et al.*, 2013; Velazquez-Rodriguez *et al.*, 2012). The estimated reduction in the aragonite saturation state is also given in the tables.

Higher spatial and temporal frequency and coherent monitoring approaches should enhance the ability to detect and compare acidification trends in the North Atlantic.

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Table 1. Long-term changes of OA parameters in surface waters of the OSPAR region, taken from the literature. Values in normal font are the published values, while in italics are calculated using CO2SYS based on supporting data in the same paper. The type of time-series or repeated observations are (A) Sustained Ocean Time-Series (Monthly/Seasonal Sampling); (B) Annual re-occupied transects/sites; (C) Low frequency Re-occupation of previous transect and (D) Opportunistic broadscale surface sampling. For the ΔpH, (T) indicates total pH scale, and (S) the seawater scale.

Type	Area	Location	Region	Time	ΔpCO2 µatm yr-1	ΔDIC µmol kg-1 yr-1	ΔnDIC µmol kg-1 yr-1	ΔpH (units yr-1)	Δ ΩAr	Measurements	Reference
A	Iceland Sea (winter)	68N, 12.66W	I	1985–2008	2.1 ±0.2	1.4 ± 0.2		-0.0024 ±0.0002 (T)	-0.0072 ±0.0007	DIC, pCO_2	Olafsson *et al*., 2009
A	Iceland Sea	68N, 12.66W	I	1983–present	1.3 ±0.4	1.2 ± 0.3	0.9 ± 0.2	-0.0014 ±0.0005 (T)	-0.0018 ±0.0027	DIC, pCO_2	Bates *et al*., 2014
A	Irminger Sea	64.3N, 28W	I	1983–present	2.4 ±0.5	1.6 ±0.4	1.5 ± 0.4	-0.0026 ±0.0006 (T)	-0.0080 ±0.0040	DIC, pCO_2	Bates *et al*., 2014
A	BATS Sargasso Sea	32N, 64W	*	1983–present	1.7 ±0.1	1.4 ±0.1	1.1 ± 0.0	-0.0017 ±0.0001 (T)	-0.0095 ±0.0007	DIC, TA	Bates *et al*., 2014
A	ESTOC Canary Is	29.04N, 15.50W	*	1995–present	1.9 ±0.2	1.1 ±0.1	1.1 ± 0.1	-0.0018 ±0.0002 (T)	-0.0115 ±0.0023	DIC, TA	M. Gonzalez-Davila M. Santana-Casiano Bates *et al*., 2014
B	PAP	49N, 16.5W	V	2003–2011	1.8					pCO_2	Hartman *et al*., 2014
B	Norwegian Sea	66N, 2E	I	2002–2006	2.6 ± 1.2 *3.0*	1.3 ± 0.7		*-0.0030 (T)*	*-0.0115*	DIC, assume constant TA	Skjelvan *et al*., 2008
C	Rockall Trough		V	1991–2010	2.1	1.3 ± 0.6	1.0	-0.0020 (T)	-0.0083	DIC, TA	McGrath *et al*., 2012
C	Nordic Seas		I	1981–2002	1.2–2.4 ±0.4		0.2–0.9			DIC	Olsen *et al*., 2006
C	North Sea		II	2001–2005	5.5	5.0	3.0	*-0.0064 (T)*	*-0.0710*	DIC, pCO2 Estimated TA	Thomas *et al*., 2007
D	NE Atlantic		V	1981–2007				-0.0022 ±0.0004 (S@25ºC)		SOCAT fCO_2 Estimated TA	Lauvset and Gruber, 2014

TYPE	AREA	LOCATION	REGION	TIME	ΔPCO2 µATM YR−1	ΔDIC µMOL KG−1 YR−1	ΔNDIC µMOL KG−1 YR−1	ΔPH (UNITS YR−1)	Δ ΩAR	MEASUREMENTS	REFERENCE
D	NE Atlantic Celtic Sea Bay of Biscay		V, III IV	1990–2006	1.6 ± 0.2 (fCO_2)					fCO_2	Schuster *et al.*, 2009
D	Celtic Sea		IV	1990–2006	3.2 ± 0.3			-0.0032		fCO_2	Schuster *et al.*, 2009 ICES, 2013
D	N Atlantic Basin		I V	1972–2005	1.8 ± 0.4					Mix of datasets	Takahashi *et al.*, 2009
D	N Atlantic		I, II, III, V	1991–2011	± 0.2 (fCO_2)			*-0.0020 ±0.0004(T)*		fCO_2, Calculated TA	Lauvset *et al.*, 2014

***Outside OSPAR regions but in wider N. Atlantic.**

Extra notes on the table and calculations:

Bates *et al.* (2014). It is assumed that nDIC was used in the calculation of pH and Aragonite saturation.

Hartman *et al.*, 2014. Only pCO_2 was reported. It is likely that other carbonate parameters are sampled on surveys to the PAP site.

Skelvan *et al.*, 2008. Surface winter DIC of 2140µmol kg^{-1} was reported, with an increase in nDIC of 1.3 µmol kg^{-1} per year between 2002 and 2006. A constant alkalinity of 2320 µmol kg^{-1} was used for both years in the calculations. The ΔpCO_2 (3.0 µatm yr^{-1}) calculated from the nDIC (given) and constant TA was higher than the rate of increase of 2.6 µatm yr^{-1} published in the paper.

McGrath *et al.*, 2012. The change in pH and aragonite between 1991 and 2010 was calculated by adding the increase in anthropogenic DIC (calculated in paper using DIC, oxygen and nutrient data), which was 18 µmol kg^{-1} over the 19 years, to the DIC measured in 1991.

Olsen *et al.*, 2006. Only anthropogenic DIC was reported in this paper, with 'equivalent' pCO_2 increase. There was a wide range of ΔCant in surface waters, largest associated with the Atlantic domain of the Nordic Seas (0.9 µmol kg^{-1} yr^{-1}).

Thomas *et al.*, 2007. nDIC, pCO_2 and temperature were given for 2001 and 2005, which were used to calculate pH_T and aragonite saturation changes. The annual rate of pCO_2 increase, calculated here from numbers in the abstract, is higher here than Table 2.3 in the ICES 2013 report, based on the same paper.

Lauvset and Gruber, 2014. Used fCO_2 from SOCAT and estimated TA from the Lee *et al.* (2006) algorithm to calculate pH. The reported pH is on the seawater scale at 25ºC.

Schuster *et al.*, 2009. Used fCO_2 from BATS, ESTOC and a number of voluntary observing ship lines in the North Atlantic. The trend of +1.6µatm yr^{-1} was for the entire area using all data sources. Just looking at the Celtic Sea, a rate of increase in fCO_2 was 3.2 µatm yr^{-1} was estimated, which was equivalent to an annual decrease in pH of -0.0032 (calculated using constant alkalinity; in ICES 2013, unsure what pH scale).

Lauvset *et al.*, 2014. Used fCO2 observations from the SOCATv2 and surface total alkalinity estimates based on temperature and salinity. pH was calculated on the total scale at *in situ* temperature.

Table 2. Long-term changes of OA parameters in some interior ocean water masses in the OSPAR region, taken from the literature. The pH from Vázquez-Rodríguez *et al*. (2012) were measured values on the seawater scale, while DIC, pCO_2 and Aragonite saturation are calculated using CO_2SYS with the pH (seawater scale) and TA calculated from the Lee *et al*. (2006) algorithm. The carbonic acid dissociation constants of Mehrbach *et al*., 1973 refit by Dickson and Millero, 1987 were selected. pH in McGrath *et al*., 2012 was calculated on the total scale (T) from measured DIC and TA values.

Basin	OSPAR Region	Time	Water Mass	ΔpHsws/yr	ΔDIC/yr	ΔpCO2/yr	ΔAr/yr	Measurements	Reference
Irminger Sea	I	1981–2008	SAIW	-0.0011	*0.4*	*2.3*	*-0.0009*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)
Irminger Sea	I	1981–2008	cLSW	-0.0016	*0.5*	*2.8*	*-0.0024*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)
Irminger Sea	I	1981–2008	uNADW	-0.0014	*0.4*	*2.2*	*-0.0021*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)
Irminger Sea	I	1981–2008	DSOW	-0.0016	*0.5*	*2.4*	*-0.0017*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)
Iceland Basin	I & V	1981–2008	SPMW	-0.0025	*0.8*	*4.5*	*-0.0073*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)
Iceland Basin	I & V	1981–2008	cLSW	-0.0009	*0.3*	*1.6*	*-0.0018*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)
Iceland Basin	I & V	1981–2008	uNADW	-0.0010	*0.3*	*1.6*	*-0.0014*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)
ENA Basin	V	1981–2008	NACW	-0.0013	*0.6*	*2.1*	*-0.0037*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)
ENA Basin	V	1981–2008	MW	-0.0006	*0.3*	*1.1*	*-0.0007*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)
ENA Basin	V	1981–2008	cLSW	-0.0009	*0.2*	*1.4*	*-0.0021*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)
ENA Basin	V	1981–2008	uNADW	-0.0002	*0.1*	*0.4*	*-0.0003*	pHsws at 25ºC and TA estimated from Lee *et al*. (2006)	Pérez *et al*. (2010) Vázquez-Rodríguez *et al*. (2012)

BASIN	OSPAR REGION	TIME	WATER MASS	ΔpHSWS/YR	ΔDIC/YR	ΔpCO2/YR	ΔAR/YR	MEASUREMENTS	REFERENCE
Rockall Trough	V	1991–2010	cLSW	(T)-0.0015	0.5		-0.0058	DIC, TA pH calculated on total scale.	McGrath *et al*. (2012)

ENA East North Atlantic, Water Masses: DSOW Denmark Strait Overflow Water; cLSW central Labrador Sea Water; MW Mediterranean Water; NACW; North Atlantic Central Water; uN-ADW upper North Atlantic Deep-water; SAIW SubArctic Intermediate Water; SPMW SubPolar Mode Water.

References

Bates, N. R. 2012. Multi-decadal uptake of carbon dioxide into subtropical mode water of the North Atlantic Ocean. Biogeosciences, 9: 2649–2659.

Bates, N.R., Astor, Y.M., Church, M.J. Currie, K. Dore, J.E., González-Dávila, M., Lorenzoni, L., *et al.* 2014. A time-series view of changing ocean chemistry due to ocean uptake of anthropogenic CO2 and ocean acidification. Oceanography 27(1):126–141, http://dx.doi.org/10.5670/oceanog.2014.16.

Canadell, J.G., Le Quéré, C. Raupach, M.R., Field, C.B., Buitenhuis, E.T., Ciais, P., Conway, T.J., *et al*. 2007. Contributions to accelerating atmospheric CO(2) growth from economic activity, carbon intensity, and efficiency of natural sinks. Proceedings of the National Academy of Sciences of the United States of America 104: 18866–18870.

Corbière, A., Metzl, N., Reverdin, G., Brunet, C., and Takahashi, T. 2007. Interannual and decadal variability of the oceanic carbon sink in the North Atlantic Subpolar Gyre. Tellus B 59: 168–178.

Doney, S.C., Fabry, V.J., Feely, R.A., and Kleypas, J.A. 2009. Ocean acidification: The other CO_2 problem. Annual Rev. Mar. Sci., 1, doi: 10.1146/annurev.marine.010908.163834, 169–192.

Feely, R.A., Doney, S.C. and Cooley, S.R. 2009. Ocean acidification: Present conditions and future changes in a high-CO_2 world. Oceanography, *22*(4): 36–47 doi: 10.5670/oceanog.2009.95.

Friedrich, T., Timmermann, A., Abe-Ouchi, A., Bates, N. R., Chikamoto, M. O., Church, M. J., Dore, J. E., *et al.* 2012. Detecting regional anthropogenic trends in ocean acidification against natural variability. Nature Climate Change, 2: 167–171.

Hartman, S. E., Jiang, Z.-P., Turk, D., Lampitt, R. S., Frigstad, H., and Ostle, C. 2014. Biogeochemical variations at the Porcupine Abyssal Plain Sustained Observatory (PAP-SO) in the northeast Atlantic Ocean, from weekly to inter-annual time scales. Biogeosciences Discuss., 11: 12415–12439.

Hydes, D. J., McGovern, E., and Walsham, P. 2013. Chemical aspects of ocean acidification monitoring in the ICES marine area. Technical Report, ICES Cooperative Research Report No. 319. 78pp. International Council for the Exploration of the Sea.

Lauvset, S. K., and Gruber, N. 2014. Long-term trends in surface ocean pH in the North Atlantic. Marine Chemistry, 162: 71–76.

Lauvset, S. K., Gruber, N., Landschützer, P., Olsen, A., and Tjiputra, J. 2014. Trends and drivers in global surface ocean pH over the past three decades. Biogeosciences Discuss., 11: 15549–15584.

Le Quéré, C., Moriarty, R., Andrew, R. M., Peters, G. P., Ciais, P., Friedlingstein, P., Jones, S. D., *et al.* 2014. Global Carbon Budget 2014, Earth System Science Data Discussions, 7: 521–610 DOI:10.5194/essdd-7-521-2014.

McGrath, T., Kivimäe, C., Tanhua, T., Cave, R. R., and 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.

Olsen, A., Omar, A.M., Bellerby, R.G.J., Johannessen, T., Ninnemann, U., Brown, K.R., Olsson, K.A., *et al*. 2006. Magnitude and origin of the anthropogenic CO_2 increase and 13C Suess effect in the Nordic seas since 1981. Global Biogeochemical Cycles 20: GB3027.

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

Pérez, F. F., Mercier, H., Vazquez-Rodriguez, M., Lherminier, P., Velo, A., Pardo, P. C., Roson, G. *et al.* 2013., Atlantic Ocean CO_2 uptake reduced by weakening of the meridional overturning circulation, Nature Geosci, *6*(2): 146–152.

Pérez, F. F., Vázquez-Rodríguez, M., Mercier, H., Velo, A., Lherminier, P., and Ríos, A. F. 2010. Trends of anthropogenic CO_2 storage in North Atlantic water masses. Biogeosciences, 7: 1789–1807.

Pérez, F. F., Vazquez-Rodriguez, M., Louarn, E., Padín, X. A., Mercier, H. and Ríos, A. F. 2008. Temporal variability of the anthropogenic CO_2 storage in the Irminger Sea., Biogeosciences, *5*: 1669–1679.

Resplandy, L., Bopp, L., Orr, J. C., and Dunne, J. P. 2013. Role of mode and intermediate waters in future ocean acidification: Analysis of CMIP5 models. Geophysical Research Letters, 40: 3091–3095.

Schuster, U., Watson, A.J. Bates, N.R., Corbiere, A., Gonzalez-Davila, M., Metzl, N., Pierrot, D. *et al.* 2009. Trends in North Atlantic sea-surface fCO_2 from 1990 to 2006. Deep Sea Research Part II: Topical Studies in Oceanography 56: 620–629.

Skjelvan, I., Falck, E., Rey, F., and Kringstad, S. B. 2008. Inorganic carbon time series at Ocean Weather Station M in the Norwegian Sea. Biogeosciences, 5: 549–560.

Takahashi, T., Sutherland, S.C., Wanninkhof, R., Sweeney, C., Feely, R.A., Chipman, D.W., Hales, *et al.* 2009. Climatological mean and decadal change in surface ocean pCO_2, and net sea–air CO_2 flux over the global oceans. Deep Sea Research Part II: Topical Studies in Oceanography 56: 554–577.

Tanhua, T., N.R. Bates, A. Körtzinger. 2013. The marine carbon cycle and ocean carbon inventories. Siedler, G., Griffies, S., Gould, J. and Church, J. (Eds.): Ocean Circulation and Climate, 2nd Ed. A 21st century perspective, Academic Press, 103: 787–815, doi.org/10.1016/B978-0-12-391851-2.00030-1.

Thomas, H., Friederike Prowe, A.E., van Heuven, S., Bozec, Y., de Baar, H.J.W., Schiettecatte, L.-S., Suykens, K. *et al.* 2007. Rapid decline of the CO_2 buffering capacity in the North Sea and implications for the North Atlantic Ocean. Global Biogeochemical Cycles 21: GB4001.

Thomas, H., Friederike Prowe, A.E., Lima, I.D., Doney, S.C., Wanninkhof, R., Greatbatch, R.J., Schuster, U. *et al.* 2008. Changes in the North Atlantic Oscillation influence CO_2 uptake in the North Atlantic over the past two decades. Global Biogeochemical Cycles 22: GB4027.

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