Science and Technology Select Committee: Inquiry into ocean acidification
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Response from the National Oceanography Centre

The National Oceanography Centre (NOC) is the United Kingdom's centre of excellence for oceanographic sciences. The NOC has a remit to provide national capability and leadership for big ocean science.

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1. The role of increased CO_2 emissions, and any other drivers or feedback mechanisms, on ocean acidification.

1.1 Ocean acidification describes the ongoing decrease in ocean pH caused by human CO_2 emissions, such as the burning of fossil fuels. Currently, the oceans absorb approximately half to a third of the CO_2 produced by burning fossil fuels; put simply, atmospheric CO_2 would be far higher if not for the ocean. . However, there is a cost; when CO_2 dissolves in seawater it forms carbonic acid and as more CO_2 is taken up by the ocean's surface, the pH decreases, moving towards a more acidic state.

1.2 Already surface ocean pH has decreased by about 0.1 units and if we continue emitting CO_2 at the same rate by 2100 ocean acidity will increase by a further 0.3-0.4 pH units. Such an alteration in basic ocean chemistry is likely to have wide implications for ocean life, especially for organisms that require calcium carbonate to build shells or skeletons (UK Ocean Acidification Programme).

1.3 Ocean acidification cannot be considered in isolation. Concurrent changes in global temperatures provide additional stressors compounding the potential effects of ocean acidification. For example, increased seawater temperatures have a negative influence on tropical corals, which are then trying to also adapt to changes in seawater pH. Furthermore, increased Arctic temperatures result in higher riverine supplies of terrestrial organic matter to coastal ecosystems which is converted back to CO_2 providing localised positive feedback to ocean acidification.

1.4 Whilst analysis of climate models, such as those used in IPCC assessments, provide robust evidence of the future change in ocean pH, as well as additional stressors, whereas unravelling the consequences for marine organisms and ecosystems remains at the frontier of marine science. Organisms may adapt, acclimate or migrate in response to ocean acidification and other climate effects, but the complexity of the marine ecosystem restricts our ability to make quantitative assessments of when, where and what the impacts on individual components of the ecosystem will be.

1.5 Although there are still significant gaps in our knowledge of ocean acidification that make parameterising its impacts difficult, ocean models have begun including representations of these. In a UK Ocean Acidification Programme study using the MEDUSA model, Yool et al. (2013) found that acidification may unexpectedly impact deep sea communities more than those in the surface ocean because it could diminish the calcium carbonate that currently "ballasts" the sinking organic material that they rely on for food. Other modelling studies, such as that of Tagliabue *et al*. (2011), have highlighted how current uncertainty in ocean acidification impacts leads to a broad spread of possible future impacts.

2 Whether ocean acidification and its impact varies regionally.

2.1 Ocean acidification, and other stressors, need to be considered in the light of natural variability. Organisms and ecosystems are adapted to the range of normal conditions they experience, whether that be the ocean's pH, temperature, or other factor. Climate model analyses suggest that ocean acidification and warming both exceed the range of natural variability very rapidly over much of the ocean within the next 15 years. The development of stress due to de-oxygenation and a loss of overall productivity emerge more slowly, but nevertheless by the end of the century more than half of the ocean surface is predicted to experience multiple sources of stress. Subtropical regions, the Arctic and the northeast Atlantic are predicted to be most rapidly affected by multiple stressors, including ocean acidification, with the Southern Ocean and South Pacific more slowly affected (Henson *et al.* 2017).

2.2 The impacts on marine ecosystems are expected to vary regionally, depending on the structure of the ecosystem, the sensitivity of its biological components, and their ability to adapt, acclimate or migrate. In many regions of the ocean even the basic ecosystem structure is poorly known, and very little information exists on the adaptation, acclimation or migration potential of individual organisms, or what the overall effect on a region's ecosystem could be (Henson *et al.* 2017).

2.3 While atmospheric CO2 dissolves into seawater throughout the ocean, because of the underlying carbonate chemistry, the effects of this on ocean pH are greatest in cooler, polar waters, where CO_2 uptake by the ocean is greatest (Orr *et al*. 2005). However, even in polar waters, regional aspects of circulation, biogeochemistry and hydrology (water cycle relations) can be important. For instance, in the Arctic Ocean, spatial and temporal patterns of acidification, mean that the basin is a "sea of contrasts" that make it difficult to produce overarching impact statements for even this limited area (Popova *et al*. 2014).

3. The main socio-economic, industry, ecosystem and environmental impacts of ocean acidification.

3.1 Example of socio-economic impact

In October 2014 the U.N. Convention on Biological Diversity released a report updating the impacts of ocean acidification on marine life. It put estimated costs on the predicted damage, hoping to make national governments aware of the potential costs size of the various threats. While many of the effects of growing acidification remain invisible, by the end of this century, things will have changed drastically, the report found. One estimate, looking only at lost ecosystem protections, such as that provided by fringing tropical reefs, cited an economic value of $1 trillion annually (Huizen 2014).

3.2 Examples of environmental impact

A large number of experimental studies have been undertaken on the response of organisms and ecosystems to ocean acidification.

Kroeker *et al*. (2013) reviewed these for a number of key biological groups, and reported positive, negative and neutral (or ambiguous) responses to acidification. They also found significant gaps in knowledge for a number of groups, as well as a trend towards enhanced sensitivity to acidification when combined with elevated temperatures.

By tipping the balance of ecological competition, ocean acidification may be helping invasive species of harmful algae, jellyfish, crabs and shellfish to move to new areas of the planet with damaging consequences for ecosystems and coastal populations(Ocean Acidification Programme).

Experimental simulation of future ocean conditions shows that the skeletons of deep-sea corals change shape and become 20-30% weaker, putting deep-sea biodiversity at risk as these organisms provide essential habitat for deep-sea life (Ocean Acidification Programme).

3.3 Examples of impact on industry

Fitness and survival of commercially-important shellfish may be at risk from ocean acidification, including species-specific impacts on their immune systems and metabolic balance (Ocean Acidification Programme (Fisheries)).

Ocean acidification resulting from human emissions of carbon dioxide has already lowered and will further lower surface ocean pH. The consequent decrease in calcium carbonate saturation potentially threatens many calcareous marine organisms. For example, it has been demonstrated that the calcification rates of the edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) decline linearly with increasing pCO_2. Mussel and oyster calcification may decrease by 25 and 10%, respectively, by 2100, following the IPCC IS92a scenario (~740 ppmv in 2100). Moreover, mussels dissolve at pCO_2 values exceeding a threshold value of ~1800 ppmv. As these two species are important ecosystem engineers in coastal ecosystems and represent a large part of worldwide aquaculture production, the predicted decrease of calcification in response to ocean acidification will likely have an impact on coastal biodiversity and ecosystem functioning as well as potentially leading to significant economic losses (Gazeau *et al.* 2007)

4. The level of understanding of the processes and impacts of ocean acidification

4.1 The chemical reactions and process whereby increased atmospheric CO_2 alters ocean chemistry, including changes in pH and the basic chemistry of other chemical constituents in sea water, is well known and current understanding allows predictability. This high level of understanding is demonstrated with the clear interpretations available of observations. Although as observing networks intensify and expand into poorly sampled areas (e.g. polar oceans, tropical coastal ocean), via advances in technology (autonomy) and international collaboration (ODA) new insights are being gained. Furthermore, chemical interactions between ocean acidification driven changes in ocean chemistry, such as the forms of key elements required for growth, is only recently being realised and studied. For example, an ocean acidification chemically-induced change in nutrient status of the ocean would directly influence ocean productivity and ecosystem sustainability.

4.2 While our understanding of the chemical processes of atmospheric CO_2 interaction with the ocean and ocean acidification are well established, despite numerous international efforts, the level of understanding of the impacts of ocean acidification is still limited. Although we have made significant gains in understanding the potential sensitivity and physiology of different marine organisms, difficulties in realistic experimental design and a failure to fully appreciate the compounding environmental factors (multi-stressors) leaves much research still to do.

4.3 Early challenges for experimental design ranged from the need to replicate and standardise to avoid confounding results from similar (rather than identical) experiments, to the acknowledgement that real-world ocean acidification occurs over decades to centuries whereas most experiments last only a few days, weeks or (rarely) months. Though standardisation has improved across experiments, consideration of the time-scale of experiments remains as a challenge to the application of results from short-term experiments to long-term changes.

4.4 Today’s challenges now include how to scale small-scale experiments in controlled laboratory conditions to the more heterogeneous and variable real-world. For example, for several key groups of marine plankton we now have excellent understanding of their physiological response to variability in pH in laboratory experiments, however translating this to their response in the open-ocean is not linear due to environmental complexity and confounding factors (i.e. environmental factors which act in tandem (with pH) to influence an organisms growth and survival, termed ‘multi-stressors’; (Boyd *et al*., 2015). From these issues stem much of the scientific debate around the impact of ocean acidification on marine ecosystems – the perfect scientific experiment has not yet been designed or implemented.

4.5 The 2016-17 MCCIP report (Williamson *et al.* 2016) on ocean acidification identified several ‘emerging issues’ that warrant further research, including: using novel techniques (e.g. Free-ocean CO_2 enrichment) to vary experimental conditions, such as raising (rather than lowering) pH levels or varying pH and other carbonate chemistry parameter independently; multi-stressor interactions (pH, temperature, toxic metals, oxygen and food supply); sensitivity of the aquaculture industry (possibly through academic-industrial partnerships); potential for genetic adaptation through evolutionary processes and their molecular basis; potential impacts of the large-scale removal.

5. The gaps in terms of monitoring, prevention, mitigation, and adaptation

5.1 The effects of ocean acidification are complex and cannot be considered in isolation from other stressors that affect biodiversity and ocean health (Gehlen *et al.* 2014). The combinations of change that can occur across multiple stressors including pH, temperature, oxygen, and primary production can also vary regionally and with time (Mora *et al*. 2013). However, the ways in which multiple stressors might manifest in changes in ocean ecosystem function is poorly known (Boyd *et al*., 2015; *Henson et al*., 2017).

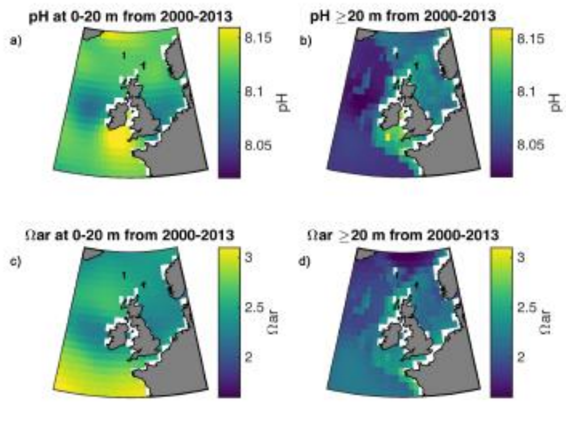

Figure 3.13: Maps of pH and aragonite saturation state (Ωar) from GLODAP V2 climatology (Lauvset *et al.*, 2016). **a)** pH from 2000 to 2013 between 0 m and 20 m. **b)** pH from 2000 to 2013 deeper than 20 m. **c)** Ωar from 2000 to 2013 between 0 m and 20 m. **d)** Ωar from 2000 to 2013 deeper than 20 m.

Figure shows patchy pH values around the NW European shelf (Ostle *et al.* 2016)

5.2 Advances in technology enable understanding of the interaction between variables that influence ocean chemistry, for example. A recommendation from a report by Williamson *et al.* 2016, is that new sensors and platforms (gliders and profiling floats) currently under development are further tested, and used to increase the cost-effectiveness and spatial coverage of ocean acidification measurements in UK waters. Such an intensification of monitoring carbonate chemistry in UK coastal waters would allow better understanding of the variability observed and require continuation of existing ocean acidification time series, as well as the measurement of other parameters, dedicated effort on data interpretation, and development of guidelines for cost-effective integrated biogeochemical monitoring to meet policy needs.

5.3 A report by Williamson *et al.* 2016 made further recommendations, including further research to support: (1) Development of a *UK marine monitoring strategy,* including cost-effective (autonomous) ocean acidification measurements within an integrated marine observing network, to meet national and international policy needs; (2) Development of a *marine monitoring strategy for British Overseas Territories*, including cost-effective ocean acidification measurements in the context of conservation needs (e.g. stewardship of Marine Protected Areas), such as that developed by the US NOAA which includes autonomous sensor packages adapted to meet site-specific needs. Both of these initiatives would vastly enhance opportunities for (UK lead) global data synthesis and improved scientific understanding.

5.4 The UK, via the NOC, is currently leading in the construction of pH–enabled systems and is at the forefront of autonomous observation systems for ocean acidification measurements. The NOC (and UK) also leads the development of high precision pH sensors and sensors for other carbonate system parameters, such as Dissolved Inorganic Carbon (DIC) and Total Alkalinity (TA).

5.5 These systems based on 'lab on chip' technology, employ state of the art laboratory analysis techniques which enables resolution of annual carbonate system changes attributable to anthropogenic CO_2 increase - for example, the NOC pH sensor has a resolution of 0.0003 pH (0.3 mpH) versus an annual anthropogenic signal of 0.002 pH (2 mpH). These high-sensitivity sensors have been integrated into autonomous gliders (e.g. in collaboration with the University of East Anglia) and on the NOC long range Autonomous Underwater Vehicle (AUV; Robotic Submarine) Autosub Long Range (ALR). This technology is being developed for a number of applications (see sections 7.4 and 7.5), though to operationalise this technology requires a company to manufacture and support the sensors and organisations to undertake the operational observation of ocean pH (Rérolle e*t al.* 2012, Rérolle *et al.* 2013).

5.6 The 2015 Paris Agreement has set a global action plan to put the world on track to avoid dangerous climate change by limiting global warming to well below 2ºC, however, there is a need for better understanding of how the climate mitigation measures will alter the magnitude and/or impacts of ocean acidification on marine ecosystems (Williamson, P. *et al.* (2016)).

6. Monitoring adaptation

6.1 The legacy of ocean acidification is likely to be of winners and losers in marine ecosystems. Experimental and observational data has highlighted a large potential for many marine species to adapt to ocean acidification, although the speed of change can determine whether species exhibit shock responses, acclimation or eventual adaptation. The life-span of organisms also impacts on such responses, for example fast-growing organism may adapt faster than slower growing ones.

6.2 Monitoring responses and eventual adaptation in marine ecosystems is possible and would closely align with current international efforts to monitor and observe ongoing ocean acidification changes on daily to decadal time-scales. Such a strategy would need to recognise that ocean acidification is occurring in a melting pot of environmental variability and change, on short and long term time-scales, and would need to be able to decompose the different signals and drivers of change – though the scientific community is well versed in rising to these challenges. For example, the 'RAPID-AMOC' Programme involved the UK science community, working with international colleagues, to monitor and quickly and effectively assess the risk of the Atlantic Meridional Overturning Circulation (AMOC) collapse (RAPID: http://www.rapid.ac.uk/)

7. The impact of previous UK research work, and the sufficiency of research currently underway.

7.1 The £12M five year UK Ocean Acidification Programme (2009 – 2014), was funded by DECC, Defra and NERC and involved 23 UK scientific and academic institutes. The impacts of this programme are numerous and include, for example, a new understanding of the rate of ocean acidification, following collaboration with US researchers; an indication that there will be a likely loss of familiar seaweeds under the combined effects of warming and ocean acidification and the inclusion of ocean acidification in the draft Global Calculator. UK scientists Carol Turley and Phil Williamson were invited to give presentations at the major US conference *Our Ocean.* The US government invited UKOA representation to a follow-up science-to-policy meeting.

7.2 UK Ocean Acidification (OA) scientists have been involved in major conferences and meetings, including the Oceans Sciences meetings, the Transboundary Waters Assessment Programme, the Ocean Acidification International Co-ordination Centre workshop. A list of programme outputs is given in the 2014 Ocean Acidification Biannual Achievements Report (UKOA 2014).

7.3 The UK-Integrated Carbon Observation System (ICOS) (2014 – 2018) is part of the European Strategy forum on Research Infrastructure and consists of a network of European observing systems operated at member state level. The ICOS Ocean Thematic Centre includes UK members: the NOC, Plymouth Marine Laboratory and the University of Exeter. The European Multidisciplinary Seafloor and water-column Observatory (EMSO) also contributes to research of ocean acidification in combination with the study of processes across marine geology, ocean physics, biogeochemistry and marine ecology.

7.4 Through EPSRC, NERC, EU (FP7 and H2020) and direct industry funding (Energy Technologies Institute, BP) the NOC has developed a near operational (Technology Readiness Level 7) pH sensor with accuracy as good as the available pH standards which can be submersed to up to 6000 m (i.e. full ocean depth). This has been integrated with autonomous ocean gliders, and with the NOC's Autosub Long Range AUV (see sections 5.2 and 5.3).

7.5 The pH sensor technology is now the subject of innovation funding to enable transfer to industry and mass manufacture. This will provide a commercially available pH sensor technology able to resolve annual variability and trends in ocean acidification over wide swaths of the ocean. The sensor also supports the development of a commercial system for leak detection and quantification from ocean carbon capture and storage reservoirs (ETI CCS MMV project and H2020 STEMM-CCS project). These projects have also supported the development of DIC and TA sensors currently.

8. What areas of Government policy-making are currently held back by insufficient knowledge/evidence on ocean acidification, and the risks this poses?

8.1 Ocean acidification is only one of many challenges for the ocean and marine ecosystems. As the climate changes, the marine environment is subjected to changes in biological, chemical and physical processes. These changes can reduce ecosystem resilience to other man-induced pressures (e.g. pollution), leaving ecosystems increasingly sensitive to disruption. Impacts include rising sea levels, increased sea temperatures, precipitation changes, invasive species and ocean acidification.

8.2 Although some of the likely impacts of climate change in marine and coastal regions can be anticipated, the extent and location of these impacts is more difficult to predict with any certainty. Little is known, for example, about the effect of ocean acidification on coastal carbon sequestration and consequential effects on marine food webs and ecosystems. Furthermore, the connections between river water quality, estuarine carbonate chemistry and coastal ocean acidification are currently poorly known. Marine strategies in some coastal areas also need to identify ways of adapting to the effects of global warming and to reduce the vulnerability of natural and human systems to climate change effects.

8.3 The main goal of the Marine Directive is to achieve Good Environmental Status (GES) of EU marine waters by 2020 where GES is defined as, "… *ecologically diverse and dynamic oceans and seas which are clean, healthy and productive".* This EU legislative instrument contains the explicit regulatory objective that "biodiversity is maintained by 2020", as the cornerstone for achieving GES.

8.4 The Directive enshrines, in a legislative framework, the ecosystem approach to the management of human activities having an impact on the marine environment, integrating the concepts of environmental protection and sustainable use (EC 2016). Scientific understanding of the stressors that interact and influence the ocean and its ecosystems, will be essential in enabling member states to deliver the EU Marine Directive.

8.5 The Global Challenges Research Fund (GCRF) is providing funding for Official Development Assistance (ODA) that will enable researchers to work with scientists in developing countries, to underpin research in, for example, the impacts of ocean acidification on coral reefs. Coral reefs have both important ecological and economic value, in terms of revenue from tourism and development of the 'blue economy'. A recommendation of the MCCIP 2016-17 report (Williamson *et al.* 2016) was the possible inclusion of using UK knowledge and expertise in ocean acidification measurement and modelling to assist in the *implementation of UN Sustainable Development Goal 14* (to *"*Conserve and sustainably use the oceans, seas and marine resources for sustainable development") in the context of ODA and the GCRF. A comprehensive assessment of ocean acidification risks in the British Overseas Territories (and their Marine Protected Areas) is also needed. Furthermore, a UK offer of co-chairing the Informal Preparatory Groups for SDG 14.3 (on ocean acidification) is likely to be very well-received (Ostle *et al*., 2016).

9. What policy interventions are needed to tackle ocean acidification? In terms of both the known science and the uncertainties - and what the barriers are to implementation?

9.1 The Integrated Carbon Observation System (ICOS) is part of the European Strategy forum on Research Infrastructure and consists of a network of European observing systems operated at member state level. The ICOS Ocean Thematic Centre includes UK members NOC, Plymouth Marine Laboratory and the University of Exeter.

9.2 The G7 Tsukuba Communique set out actions to address SDG14, amongst other goals. The third target of SDG14 is to 'Minimize and address the impacts of ocean acidification, including through enhanced scientific cooperation at all levels'. Within the 5 Actions recommended by the Tsukuba Communique, Actions 1 and 4 address the need for improved observations of ecosystem health, including acidification. Additionally, Action 2 focusses on "an enhanced system of ocean assessment through the UN Regular Process for Global Reporting and Assessment of the State of the Marine Environment" which should "underpin and capture progress towards SDG-14 goal".

9.3 The G7 workshop held at NOC at the end of November 2017 made specific recommendations for each Action in the Tsukuba Communique. Several are relevant to ocean acidification, each given with an example of existing UK work that can contribute.

- ***Development of new biogeochemical sensors***
  Measuring acidification remains challenging, as demonstrated by the recent Wendy Schmidt Ocean Health XPrize competition to develop a next generation pH sensor. Commercial sensors have issues e.g. with drift. A UK team led by NOC has developed prototype sensors with no drift and high accuracy and precision. Accurate, reliable commercial pH sensors, such as the NOC pH sensor as referenced at 5.3 will allow acidification to be studied

and monitored more accurately using autonomous vehicles such as gliders, the ALR and BioArgo floats.

- ***Expansion of BioArgo float network***
  The US SOCCOM project (http://soccom.princeton.edu/) is already active deploying BioArgo floats equipped with pH sensors in the Southern Ocean. The UK will deploy 6 BioArgo floats with pH sensors as part of the ongoing NERC ORCHESTRA project in the Southern Ocean(https://www.bas.ac.uk/project/orchestra/)

- ***Greater use of data from commercial vessel***
  There is an existing collaboration between NOC and SWIRE focussed on equipping a container vessel on a repeating Vancouver-Brisbane route with a sensor package which includes measurement of pCO2 in surface seawater.

- ***Greater biological biogeochemical detail from augmented fixed-point observatories***
  The PAP observatory in the northeast Atlantic has been providing continuous data on ocean pH for several years and on pCO2 for a decade.

- Support for the UN World Ocean Assessment (WOA).
  The first WOA addressed the impacts of ocean acidification as part of its remit and will consider it as part of the technical abstract being prepared for the UN meetings on Sustainable Development Goals in mid-2017.

- The Arctic was one region suggested as a pilot study for capability building as part of Action 4. NERC had a recent programme on Ocean Acidification which included fieldwork and modelling of the Arctic system.

9.4 The following table shows the main statements relating to ocean acidification in the 5th Assessment Report (AR5) of the Intergovernmental Panel on Climate Change (IPCC, 2013; 2014a, b). Closely similar statements made in different parts of AR5 are combined below where confidence levels* are the same, but are kept separate if they differ. Colour shading: blue, chemistry; orange, biogeochemistry and biology (Williamson *et al.* (2016).

IPCC confidence level*	Statement	AR5 source**	Comments, update notes and UK context
Low	Fish, pelagic molluscs, foraminifera and coldwater corals vulnerable to ocean acidification at RCP 6.0 (medium emissions scenario)	WG II (A)	Vulnerability considered ‘medium’ at RCP 8.5 (high emissions scenario), except for fish, still at ‘low’. Subsequent research on fish has shown range from tolerant to vulnerable.
	Ocean acidification may affect the behaviour of fish larvae and juveniles.	WG II (A)	Effects on larval fish behaviour not studied in UKOA, but confirmed elsewhere
	Early life stages likely to be more sensitive to ocean acidification (as for other environmental stressors), but considered unproven	WG II (A)	Meta-analysis by Kroeker et al. (2013) confirmed significant life-cycle effects for molluscs; results remain ambiguous for other groups

	Ocean acidification may stimulate global net primary production	WG II (A)	High confidence level previously given for statement on photosynthesis and growth by micro-algae, but effect probably modest
	Ocean acidification may increase grazing on non-calcifying seaweeds and seagrasses due to loss of phenolic deterrent substances	WG II (A)	
	Enhanced pH reduction and variability in lowsalinity waters [e.g. estuaries, brackish seas] may constrain distributions of sensitive species	WG II (B)	
Low to medium	[For marine animals] vulnerability decreases with increasing capacity to compensate for elevated internal CO_2 concentration and falling pH	WG II (A)	
	Transgenerational or evolutionary adaptation has been shown in some species, reducing impacts of projected scenarios. Adaptation accelerated by high functional variability in offspring (and short generation time)	WG II (A)	Additional evidence from vent studies and experiments make impacts less predictable, but not necessarily of less ecological or societal importance. At vent sites, most benthic calcifiers absent; i.e. unable to adapt.
	Differential sensitivities and associated shifts in performance and distribution will change predator-prey relationships and competitive interactions	WG II (A)	Confidence level seems cautious; there has been further supporting research. If some species are affected, additional consequences would seem inevitable
Medium	[Marine] ecosystems, including cold- and warm-water coral communities, are at increasing risk of being negatively affected by ocean acidification during the next decades	WG II (A)	Confidence level seems cautious: validity of statement not in doubt (due to increased research)
	Warm-water corals, echinoderms, benthic molluscs and calcifying algae vulnerable to ocean acidification at RCP 6.0 (medium emissions scenario)	WG II (A)	Vulnerability considered to be at 'high' confidence level by WG II at RCP 8.5 (high emissions scenario)
	Cold-water corals are at risk of dissolution under ocean acidification, affecting associated ecosystems	WG II (A)	Dissolution effects likely to be limited to dead reef structures. Living corals are, however, more fragile under high CO_2 conditions (Hennige et al., 2015)
	Limitations in understanding mechanisms of effect and longterm persistence make it difficult to accurately project longterm impacts	WG II (A)	Confidence level in the statement as written could be considered high (since limitations in mechanistic understanding undoubtedly *do* make projections difficult)
	Ocean acidification affects energy metabolism; enhanced calcification can sometimes occur at the expense of growth	WG II (A)	
	Ocean acidification may stimulate global nitrogen fixation	WG II (A)	Confidence level seems higher than supported by IPCC text. Shi et al. (2012) found opposite effect
Medium to high	Coral reefs and polar ecosystems are at greatest risk from ocean acidification	Synthesis	
	Future impacts of ocean acidification range from changes in organismal physiology and behaviour to population dynamics	WG II (A)	Confidence level seems cautious: validity of statement not in doubt (due to increased research)
	Observed shell-thinning in planktonic foraminifera and in Southern Ocean pteropods may be fully or partly attributed to acidification trends	WG II (A)	Shell erosion in pteropods also now observed in low pH waters of NE Pacific, but some attribution aspects still contentious

High	The pH of surface waters has decreased by 0.1 since the preindustrial era as a result of ocean uptake of anthropogenic CO_2 from the atmosphere. Further increases in atmospheric CO_2 will further decrease ocean pH.	WG I WG II (B) Synthesis	The quoted pH decrease is a global average; observed recent changes are greatest in high latitudes and in subsurface waters. Recent North Sea decrease in pH is apparently more rapid than in North Atlantic.
	The current rate of ocean acidification is unprecedented within the last 65 million years.	WG II (B)	'Medium' confidence given by WG II to the rate being unprecedented for 300 million yr. However, higher rates did probably occur 66 million years ago, due to asteroid impact ((Tyrrell et al., 2015)
	Rising CO_2 levels will increasingly affect marine biota and interfere with ecological and biogeochemical processes. Impacts will be irreversible in medium term, affecting marine ecosystems for centuries.	WG II (A) & (B)	Very long duration of impacts (thousands of years) confirmed by new modelling studies simulating future CO_2 removal from the atmosphere.
	Ecological impacts of ocean acidification will be exacerbated by raising temperature extremes, also by de-oxygenation and local changes (e.g. pollution, eutrophication).	Synthesis	Increasing recent importance given to interactions with other stressors.
	Experiments and field observations show a wide range of sensitivities and responses within and between taxonomic groups.	WG II (A)	Biological variability confirmed by many additional studies.
	Mesocosm studies and natural analogues [CO_2 vents] show that high CO_2/low pH causes losses in diversity, biomass and trophic complexity of benthic communities.	WG II (A)	Additional CO_2 vent studies have confirmed such effects. However, most communityscale mesocosm studies have been pelagic rather than benthic.
	Warm-water corals, echinoderms, benthic molluscs and calcifying algae are vulnerable to ocean acidification at RCP 8.5 (high emissions scenario). Warm-water coral structures are at risk of dissolution.	WG II (A)	Vulnerability considered 'medium' by WG II at RCP 6.0 (medium emissions). Statement on dissolution risk for warm-water corals is based on sediment dissolution; bio-erosion may also be enhanced
	Coastal shifts in upwelling CO_2 rich waters of NE Pacific have caused larval oyster mortalities in aquaculture.	WG II (A)	Increasing atmospheric CO_2 now regarded as main factor (rather than 'coastal shifts'). Equivalent effects not observed in UK or European seas.
	Most non-calcifying plants (fleshy seaweeds and seagrasses) and micro-algae respond positively to elevated CO_2 levels by increasing photosynthesis and growth.	WG II (A)	Meta-analysis by Kroeker et al (2013) did not show significantly increased photosynthesis by either fleshy seaweeds or seagrasses, but the former did show increased growth.
Very high	[We know] the chemical response to increased CO_2 dissolving in the ocean from the atmosphere.	WG II (B)	

10. Barriers to implementation

10.1 More research and continued advances in the development of technology will be needed to enable determination of the extent of ocean acidification and its impacts, therefore, maintaining or increasing the existing level of funding support will be important. There is now some uncertainty over how funding may be impacted as a result of the UK leaving the European Union; there is uncertainty on how climate change research in the US may be impacted following the recent US election.

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