Global Biodiversity Sub-Committee (GBSC)

Thematic Report

Ocean Acidification Current research activities and known research gaps

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Ocean Acidification

Current research activities and known research gaps

Paper for the Global Biodiversity Sub-Committee of the Global Environmental Change Committee

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Ocean Acidification

1. Summary of the Issue

1.1 In recent years it has been well documented that approximately 50% of anthropogenic carbon dioxide (CO_2), released into the atmosphere has been taken up by the oceans (Sabine *et al.,* 2004). Hydrolysis of CO_2 in seawater increases the hydrogen ion concentration [H+] (Orr *et al.,* 2005) reducing pH. The ability of seawater to absorb and buffer the effects of CO_2 is due to reactions with carbonate ions. The dissolved CO_2 reacts with carbonate ions (CO_3^{2-}) to produce bicarbonate (HCO_3^-). The overall effect is a removal of carbonate ions and production of bicarbonate ions:

$$CO_2 + CO_3^{2-} + H_2O \rightarrow 2HCO_3^-$$

As additional CO_2 is absorbed, the concentration of bicarbonate ions increase, forcing an equilibrium reaction which results in the dissolution of bicarbonate and a reduction in the pH of the seawater (Turley *et al.,* 2004):

$$HCO_3^- \rightarrow H^+ + CO_3^{2-}$$

1.2 To date the pH of surface marine waters has reduced by 0.1 units. This current observed change is 100 times faster than those seen over the last 100,000 years (Haugan *et al.,* 2006). It is predicted that by 2100 the pH may have decreased by approximately 0.3 to 0.5 units under a 'business as usual' scenario (Caldeira & Wickett, 2005).

1.3 Although scientific research in this area has been underway for the last 10 years, the current understanding of the effects of ocean acidification is limited (Haugan *et al.,* 2006). There has been little political uptake although recent research outputs have provided a clear overview of the issue and the potential impacts on the marine ecosystem which have raised the profile of ocean acidification with politicians and the public alike (IOC/SCOR Symposium 2004; Royal Society report, 2005). Ocean acidification was also raised for the first time in the reports and policy summaries of both Working Group I (The Physical Science Basis, IPCC, 2007a) and Working Group II (Impacts, Adaptation and Vulnerability, IPCC, 2007b) of the Intergovernmental Panel on Climate Change (IPPC) which will contribute to the 4th Annual Assessment for climate change (expected November 2007).

1.4 Ocean acidification is anticipated to have an impact on marine organisms and the environment that they inhabit by (but not limited to) reducing calcification rates; changes to nutrient speciation; changes to phytoplankton diversity and growth; alteration of life spans; reduced tolerance to environmental fluctuation; changes to community structure and regime shifts (Turley *et al.*, 2006). There is a need to understand what these impacts are in order to ensure policies are well founded and what the interactions with the effects of climate change.

2. Current predictions of pH change

Table 1 Predicted changes in pH and Hydrogen ion concentration with increasing atmospheric pCO_2

Approximate date	Atmospheric CO_2 (μmol/mol)	Marine pH	% increase in H^+ ions
1800	260	8.2	
1880	280	8.18	5%
1900	285	8.17	7%
1950	315	8.14	15%
2000	375	8.08	32%
2050	500	7.97	70%
2100	700	7.84	130%
2150	1000	7.70	216%

(taken from Blackford *et al.,* 2007)

2.1 Acidification of the oceans is likely to continue but what is not understood is what the critical levels will be for marine organisms and ecosystems. Orr *et al.,* (2005) raised concerns over calcifiers inhabiting high latitudes (polar and sub-polar regions). Calcifiers (e.g. coccolithophores, pterpods etc) either form calcite or aragonite shells, tests or liths. It has been predicted that the surface waters of the polar regions could become under-saturated for aragonite by 2050, and for calcite by 2100, reducing the availability of compounds required for shell/test formation. The potential loss of these organisms will alter the marine food web and also impact upon rates of carbon removal from the marine ecosystem. Effects on other organisms may be more subtle, for example, the increased acidity may effect enzymes necessary for metabolic reactions and functioning.

3. Current Activities and Research

International

3.1 Researchers from around the globe are sharing current knowledge via participation in symposiums and workshops. The International Oceanographic Committee (IOC, under UNESCO) and the Scientific Committee on Oceanic Research (SCOR) organised a symposium in 2004 ‘Oceans in a High CO2 world’, a second symposium planned for 2008. A website has been set up as a source of information for researchers. The IOC and SCOR also co-sponsor the International Ocean Carbon Coordination Project (IOCCP[2]) which is an affiliate of the Global Carbon Project. The IOCCP promotes a global network of ocean carbon observation research via technical coordination and communication services, international agreements on standards and methods, and links to the global carbon observing system.

3.2 IMBER (Integrated Marine Biogeochemistry and Ecosystem Research) and SOLAS (Surface Ocean-Lower Atmosphere Study) have set up a joint SOLAS-IMBER Carbon Implementation Group (SIC) which works with the IOCCP. The SIC group has two main areas of global research:

[2] IOCCP (International Ocean Carbon Coordination Project) http://www.ioccp.org/

1. Carbon inventories, fluxes and transports; and
2. Sensitivities of carbon-relevant processes to changes occurring in the ocean.

3.3 Various experiments to assess the effects of ocean acidification on marine organisms and the ecosystem are being carried out by individual research groups at an international level. Several papers which discuss the current global research effort to date are now available (Kleypas *et al.*, 2006; Haugan *et al.*,2006).

European

3.4 CARBOOCEAN is a EU 6th Framework funded programme in which a consortium of 47 groups (including some from North America) are working together to fulfil the aim of determining the oceans quantitative role for uptake of CO_2. The focus is to gather knowledge (from historical records) in the Atlantic and Southern Oceans and to predict future uptake (over the next 200 years). The programme has 5 core themes;

1. To determine the air-sea exchange on a seasonal to inter-annual scale;
2. To detect decadal to centennial ocean carbon inventory changes;
3. To determine carbon uptake and release on a European scale;
4. To investigate biogeochemical feedbacks on the ocean-carbon sink; and
5. To look at future scenarios for marine carbon sources and sinks.

3.5 CARBOOCEAN has enabled a European monitoring network for observation of ocean and shelf sea to be observed (by University of East Anglia (UEA), UK). Additional observations are made by National Oceanography Centre (NOC) and Plymouth Marine Laboratory (PML) under Natural Environment Research Council (NERC) funded CarbonOps. There is a disparity between changes observed in-situ and predictions from numerical models. It is therefore essential that in-situ observations are maintained so that the real rate of change in the oceans is documented.

3.6 Research funded under this project has included work on the Southern Ocean and its capacity to act as a sink for CO_2. It was estimated using process models that this sink has weakened between 1991 and 2004. The weakening has been attributed to the observed increase in Southern Ocean winds and it is suggested that the trend in increased wind conditions may be caused by the depletion of stratospheric ozone and in part by changes in surface temperature gradients resulting from global warming. Such conditions are predicted to continue into the future and may result in a reduction in the efficiency of this sink (Le Quere *et al*., 2007).

3.7 European funding for the CARBOOCEAN network ceases in 2008 with no onward funding for maintenance of this network. The NERC CarbonOps observations are funded until 2009. Both networks are based on using Voluntary Observing Ships therefore the sums involved to maintain operations are relatively small.

3.8 Scientists at PML, NOC, Sir Alister Hardy Foundation for Ocean Science (SAHFOS), University of Plymouth, Scottish Association for Marine Science (SAMS), Marine Biological Association (MBA), University of Bristol, and University of Cambridge are part of an EU-wide consortium, European Project on Ocean Acidification (‘EPOCA’), which submitted a proposal to the EU 7th Framework Programme. The goal of this project is to fill a number of gaps on the understanding of the effects and implications of ocean acidification through documenting the changes in ocean chemistry and biogeography across time and space. The results from this work will be integrated into biogeochemical, sediment and coupled ocean-climate models to better understand and predict the responses of the Earth system to ocean acidification. Funding for the four year proposal was awarded late November 2007.

3.9 OSPAR (Oslo Paris) Commission for the protection of the North East Atlantic commissioned a report on the Effects on the Marine Environment of Ocean Acidification resulting from elevated levels of CO_2 in the Atmosphere (Haugan *et al*., 2006). OSPAR are however not carrying out any research per se, but are considering their response to ocean acidification, which will be discussed by the Commission in January 2008.

3.10 An ICES workshop on the significance of Changes in Surface CO_2 and Ocean pH in Shelf Sea Ecosystems was held on the 2-4th May 2007 in London (ICES WKCpH, 2007). The workshop looked at the current state of knowledge on ocean acidification and its effects on marine ecosystem components. The working group also identified future research directions relating to the spatial and temporal variability of the surface ocean pH and CO_2 – carbonate system in shelf seas. The ability to predict rates of pH and thus change in acidification levels was also discussed along with the effects of pH and the CO_2 carbonate system on nutrient chemistry, contaminants and ecosystem components (fish, plankton, shellfish, coldwater corals). A workshop summary is now available[3].

3.11 As in the international arena, individual research groups are investigating various aspects of Ocean acidification. Within the UK key research groups are working to answer scientific questions and to promote public awareness of ocean acidification. Current research being undertaken includes; the impacts of catastrophic releases on marine organism physiology, effects on the marine ecosystem (via modelling), the use of ships of opportunity to gain measurements, the effects on phytoplankton and bacteria (metagenomics study - in association with the Bergen mesocosm), Aragonite saturation in the Southern Ocean, calcification rates and effects on copepod growth and reproduction.

3.12 Research (unpublished) by the University of Plymouth on a volcanic CO_2 vent system in Italy is currently occurring. This research will provide a insight on the effects of elevated global CO_2 and why some species survive and others don't, and what the implications are for the ecosystem. The study will also provide further information on the effects of leaks from potential carbon sequestration sites. The study and assessment of this natural system is an important step forward in understanding the implications of ocean acidification on the ecosystem. Studies in the laboratory often focus on single species, so cannot assess ecosystem implications. Studies on such natural system can provide a test-bed for modelled predictions; investigate changes in settlement patterns, sediment/water nutrient flux; embryonic development; predator-prey interactions; physiological changes, survival of fish larvae, growth and reproduction success (pers. Comm. Jason Hall-Spencer, 2007).

Research Issues

[3] http://www.cefas.co.uk/science/Workshops/WKCpH/default.htm.

4.1 Research to date has generated data on the effects to marine organisms under abrupt and large changes in pH, rather than changes that could be expected from the gradual introduction of CO_2 from the atmosphere (Haugan *et al*., 2006). Most studies on the effects of elevated CO_2 have also been limited to *in vitro* shock-term experiments on isolated organisms and the use of laboratory mesocosms, with few field studies (Royal Society, 2005). Further difficulties have arisen on being able to compare the results of experiments due to the various methods to generate lower pH (CO_2 bubbling or acid addition) being used. As experiments using more realistic conditions are conducted, our knowledge on more chronic effects will grow. Initial in situ experiments have been undertaken by the Monterey Bay Aquarium Research Institute (USA), however logistics and licensing problems need to be overcome in the UK (and the EU) before further progress can be made. This type of research is also important for the consideration of impacts resulting from carbon sequestration. It is therefore important to study natural systems where they exist in order to investigate the consequences of such changes on the ecosystem.

4.2 Current changes in pH are estimated to be 0.003 pH units per year. It is difficult to accurately measure pH to this level with no accepted and readily available procedure for the monitoring of seawater pH currently available. To achieve the accuracy required, the current method calculates pH from measurements of any two of the other carbonate system parameters (pCO_2, total alkalinity, total CO_2 (also known as Dissolved Inorganic Carbon, DIC). This can pose problems as two definitions of alkalinity exist and differ in the way minor chemical species are treated; there are four pH scales (total, seawater, free and Natural Bureau of Standards – now the National Institute of Standards and Technology); and differences in the formulations of the constants K1 and K2 which are required to complete the calculation of pH. Protocols for other chemical parameters (e.g. DIC) also need to be widely propagated and adhered to. Historical datasets often don't record which parameters have been used making comparison of data difficult. In the future there is a need to ensure that the metadata, details the parameters used and accompanies the reported data (Hydes, presentation at ICES workshop, 2007).

4.3 To fully understand the overall effects of ocean acidification, a holistic approach is required. Information gained from observations (research cruises, mesocosm experiments, fixed moorings, satellite data and ships opportunity) should be fed into models addressing biogeochemical (carbon cycle) and ecosystem (functioning) questions. Long term data sets are rare and research programmes are often short term or opportunistic, making research and data fragmented and diverse. This has resulted in significant problems in attempting to make assessments on predicting effects (Blackford *et al.,* 2007).

5.4 Ecosystem model outputs require validation and parameterisation. To date there is a lack of real field and experimental data to carry this out. This is particularly problematic for the formulation of functional relationships that describe physiological responses of species and populations to environmental gradients and changes. The modelling of trophic connections is also known to be a current area of weakness (Blackford *et al.,* 2007).

5.5 Current funding for research is available to answer specific, fashionable policy questions or blue skies science, which can easily result in fragmented work and a lack of focus on the wider picture. Blackford *et al,*(2007) suggested that a more coherent funding regime is required to ensure that quality science is conducted and that collaboration between research institutes and universities is facilitated. Experiments should be designed in collaboration with researchers, modellers and statisticians to ensure data collected can be used efficiently and inform the debate. The holding of annual international workshops to bring together modellers and experimentalists would also enhance communication, encourage a synergistic approach and avoid duplication. Similarly the recent IOCCP-SOLAS-IMBER SOCOV (Surface Ocean CO_2 Vulnerability and Variability) workshop (11-14th April 2007, Paris) highlighted the need for sustained funding of the global surface ocean CO_2 network (Bakker 2007, personal communication).

6. Key Knowledge Gaps

6.1 There are significant gaps in knowledge on the effects of ocean acidification on ecosystems, communities, functioning and biogeochemical processes:

- The threshold level, over which the effects of ocean acidification apparent in an organism, are generally unknown. Individual species are likely to react differently to decreasing pH, some will adapt whilst others may decline, therefore research on the responses of a large range of species to realistic changes in pH is required. This information is vital to understand the potential for organisms to adapt or experience sub-lethal effects, which may alter growth and reproduction thus ultimately resulting in changes to the community structure. Geographical variation in the responses should also be considered;

- Experiments may provide little insight into the population, community and ecosystem impacts and the likely consequences for fisheries. Factors important for population growth and resilience, such as migration and species interactions, cannot be readily manipulated experimentally. Insights into ecosystems and fisheries impacts need confronting population and ecosystem models with long-term, large-scale monitoring data such as that collected on plankton (by SAHFOS) and of higher trophic levels (e.g. Cefas, FRS, PML). The collection of such datasets should continue to be supported. These ecosystem models need to be integrated with physical and biogeochemical models. Research into community structure and populations should consider the relative effects on different life stages. It is already known that juveniles are more sensitive to stress and other impacts, however, for broadcast spawning species it will be difficult to translate the acute laboratory response into predictions of likely population and ecosystem impacts of acidification. This is because the early life stages of broadcast spawners contribute relatively little to the overall population growth rate and resilience compared to sub-adult and adult stages (Sadovy, 2001; Dulvy *et al.,* 2003);

- The effect of increasing pH on biogeochemical processes is lacking. Many processes such as nutrient speciation, nitrification, denitrification, dimethyl sulphide production and the biological carbon pump are of global importance and any changes may have strong feedbacks on the Earth System and climate. This information is vital for building modelling and predictive tools;

- Ocean acidification should be considered alongside other human stressors. Its likely species will experience additional stressors such as increased temperatures, decreased oxygen levels, potential changes to nutrients and in the case of arctic species, increased irradiance levels due to the melting of ice;

- Improved parameterisation and validation of ecosystem models (with observational data) is vital to understand and make predictions of the impacts of ocean acidification on ecosystems in shelf seas. It is within these seas that the majority of ecosystem resources are concentrated. There is a need to understand not only the economic and social impacts of ocean acidification, but the ability to set and meet future marine obligations and commitments;

- Ocean acidification is not the only issue of concern to the marine environment. Climate change is increasing sea surface temperatures and is likely to result in cumulative or synergistic effects. Little research into the combined effects of ocean acidification and climate change has occurred to date. Fishing is the main driver of change in higher trophic levels, the impacts of ocean acidification should be considered and understood in this context;

- For coastal waters and shelf seas the background against which change in acidity will occur is poorly defined. Through a year, the range of values is likely to be large (Blackford et al., 2006). The effects may be like those of temperature changes where although there is large annual range it is the shift in the mean that has been shown to be causing ecosystem shifts. Defra is currently developing a measurement programme which will provide these data;

- Advances in technology to develop automated pH sensors, that could monitor pH at the required accuracy for a long duration is required. Such instruments would provide information on the pH fluctuations and enable underway measurements of pH to be obtained from research ships or vessels of opportunity.

Although not considered ‘research’ *per se*, there is an urgent need for the development of spatially and temporally resolved monitoring of the atmosphere and surface waters (CO_2, carbonate, alkalinity and pH) over the long term in order to validate predications, to monitor differences in regional responses, and in the much longer term to assess the impact of any remediation measures that may be established.

References

Blackford, J.C., Gilbert, F.J., (2007). 'pH variability and CO_2 induced acidification in the North Sea'. *J. Mar. Systems* **64.**

Blackford, J., Austen, M., Halloran, P., Iglesias-Rodriguez, D., Mayor, D., Pearce, D., Turley, C. (2007). 'Modelling the response of marine ecosystems to increasing levels of CO_2'. *A report to Defra arising from the Advances in Marine Ecosystem Modelling Research Workshop*, Feb 12-14, 2007. Plymouth UK.

Caldeira K., Wickett M.E. (2005). 'Ocean model predictions of chemistry changes from carbon dioxide emissions to the atmosphere and ocean'. *J. Geophys. Research.* **110,** C09So4, pp12.

Dulvy, N.K., Sadovy, Y. & Reynolds, J.D. (2003) 'Extinction vulnerability in marine populations'. *Fish and Fisheries*, **4**, 25-64.

Haugan P.M., Turley, C., Poertner H-O. (2006). 'Effects on the marine environment of ocean acidification resulting from elevated levels of CO2 in the atmosphere'. *Report to the OSPAR commission*. pp27. http://www.ospar.org/eng/html/welcome.html

Hydes, D. (2007). 'A System to Monitor pH in Shelf Seas: A presentation delivered at the ICES workshop on the significance of changing ocean CO2 and pH in shelf sea ecosystems'. A workshop report is under preparation. http://www.cefas.co.uk/science/Workshops/WKCpH/default.htm

ICES WKCpH. (2007). *Report of the Workshop on the significance of changing ocean CO_2 and pH in shelf sea ecosystems.* Editors: L. Fernand & P Brewer, 2-4 May 2007, London. Unpublished, 3rd draft report.

IOC/SCOR International Science Symposium, May 2004 Paris 'The Ocean in a high CO2 world' http://www.ioc.unesco.org/ioccp/HighCO2/2004Symposium/index.htm

IOCCP-SOLAS-IMBER Surface Ocean CO_2 Vulnerability and Variability (SOCOV) workshop, 11-14 April 2007, Paris, report in preparation. http://www.ioccp.org/

IPCC (2007a): Summary for Policymakers. In: *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D Qin, M. Manning, Z. Chen, M. Marquis, K.B. Averyt, M. Tignor and H.L Miller (eds)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA. http://ipcc-wg1.ucar.edu/wg1/Report/AR4WG1_Pub_SPM.pdf

IPCC (2007b): Summary for Policymakers. In: *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Intergovernmental Panel on Climate Change 4th Assessment Report.* http://www.ipcc.ch/SPM13apr07.pdf

Kleypas, J.A., Feely, R.A., Fabry, V.J., Langdon, C., Sabine, C.L., Robbins, L.L. (2006). 'Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifers: A Guide for Future Research', report of a workshop held 18-20 April 2005, St. Petersburg, FL, sponsored by NSE, NOAA and the U.S. Geological Survey, 88pp.

Le Quere, C., Rodenbeck, C., Buitenhuis, E., Conway, T., Langenfelds, R., Gomez, A., Labuschagnes, C., Ramonet, M., Nakazawa, T., Metzl,. N., Gillett, N. & Heimann, M. (2007). 'Saturation of the Southern Ocean CO_2 Sink Doe to Recent Climate Change'. *Science,* Vol 316, pp 1735138.

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., Yool, A. (2005). 'Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms'. *Nature* **437**:681-686.

Royal Society,(2005). *'Ocean acidification due to increasing atmospheric carbon dioxide'*. Policy document 12/05. pp60. The Royal Society, London (ISBN 0 85403 617 2).

Sabine, C.L., Feely, R.A., Gruber, N., Key R.M., Lee K., Bullister J.L, Wanninkhof R., Wong C.S., Wallace D.W.R, Tilbrook B., Millero F.J., Peng T-H., Kozyr A., Ono T., Rios A.F. (2004). 'The Oceanic Sink for Anthropogenic CO2'. *Science* **305**:367-371

Sadovy, Y. (2001) 'The threat of fishing to highly fecund fishes'. *Journal of Fish Biology*, **59A**, 90-108.

Turley, C., Nightingale, P., Riley, N., Widdicombe, S., Joint, I., Gallienne, G., Lowe, D., Goldson, L., Beaumont, N., Mariotte, P., Groom, S., Smerdon, G., Rees, A., Blackford, J., Owens, N., West, J., Land, P., Woodason, E. (2004) Literature Review; Environmental Impacts of a Gradual or Catastrophic Release of CO_2 into the Marine Environment following Carbon Dioxide Capture and Storage. Final Report to Defra. http://www2.defra.gov.uk/research/project_data/More.asp?I=ME2104&M=KWS&V=me2104&SUBMIT1=Search&SCOPE=0

Turley, C., Blackford, J., Widdicombe, S., Lowe, D., Nightingale, P.D. & Rees, A.P. (2006) Reviewing the impact of increased atmospheric CO2 on oceanic pH and the marine ecosystem. In: *Avoiding Dangerous Climate Change*, Schellnhuber, H J., Cramer,W., Nakicenovic, N., Wigley, T. and Yohe, G (Eds), Cambridge University Press, 8, 65-70.

Websites

- CARBOOCEAN - http://www.carboocean.org/
- IMBER (Integrated Marine Biogeochemistry and Ecosystem Research) http://www.imber.info/C_WG.html
- IOCCP (International Ocean Carbon Coordination Project) http://www.ioccp.org/
- IPPC (Intergovernmental Panel on Climate Change) - http://www.ipcc.ch/
- SOLAS (Surface Ocean-Lower Atmosphere Study). http://www.uea.ac.uk/env/solas/