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EXPERT MEETING TO DEVELOP A SERIES OF JOINT EXPERT REVIEW PROCESSES TO MONITOR AND ASSESS THE IMPACTS OF OCEAN ACIDIFICATION ON MARINE AND COASTAL BIODIVERSITY
Montreal, 19-20 October 2011

BACKGROUND DOCUMENT TO AN EXPERT MEETING TO DEVELOP A SERIES OF JOINT EXPERT REVIEW PROCESSES TO MONITOR AND ASSESS THE IMPACTS OF OCEAN ACIDIFICATION ON MARINE AND COASTAL BIODIVERSITY

Note by the Executive Secretary

1. Pursuant to decision X/29, paragraph 66, the Executive Secretary is convening, with financial support from the Government of Spain, an Expert Meeting to Develop a Series of Joint Expert Review Processes to Monitor and Assess the Impacts of Ocean Acidification on Marine and Coastal Biodiversity, from 19 to 20 October 2011.

2. To facilitate effective deliberation of this expert meeting, the Secretariat has commissioned a background study, with a financial support from the Government of Spain, to identify existing monitoring and scientific assessment activities at global and regional levels on the impacts of ocean acidification on marine and coastal biodiversity; assess gaps in terms of its geographic, biological and ecological coverage, and barriers to effective transmission of the results of such monitoring and assessment activities to relevant policy-making processes; and provide possible elements and approaches for considering the development of a series of joint expert review processes. The study was undertaken in collaboration with the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC/UNESCO).

3. The draft background document was circulated to the meeting participants as well as the Food and Agriculture Organization of the United Nations (FAO), the Secretariat of the United Nations Framework Convention of Climate Change (UNFCCC), the World Conservation Monitoring Centre of the United Nations Environment Programme (UNEP-WCMC), the International Coral Reef Initiative (ICRI), the Ramsar Convention on Wetlands, Antarctic Treaty, the Arctic Council as well as other UN-Ocean members for their review and comments.

4. This note is submitted as information for participants in the Expert Meeting.

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BACKGROUND DOCUMENT

For

CBD Expert Meeting to Develop a Series of Joint Expert Review Processes to Monitor and Assess the Impacts of Ocean Acidification on Marine and Coastal Biodiversity

19 – 20 October 2011, Montreal, Canada.

September 2011

Prepared on behalf of the Secretariat of the Convention on Biological Diversity by Nicola Barnard and Kristian Teleki, in collaboration with IOC/UNESCO

Contents

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Executive Summary

Ocean acidification has the potential to affect the biodiversity and function of a variety of marine ecosystems, and there is growing concern that when combined with the effects of other human activities, ocean acidification will have important consequences for resources and ecosystems that are important to society.

Research has advanced rapidly in recent years generating knowledge of the consequences and causes, and sensitivity of organisms and communities to ocean acidification. Despite variable experimental results, an overall significant negative effect has been observed on calcification, growth, survival, and reproduction, suggesting predicted ocean acidification conditions will have negative consequences for many marine organisms by the end of the century. Currently the level of evidence that some species will adapt is low.

There are still substantial knowledge gaps and uncertainties, particularly in terms of the biogeochemical impacts, and implications of ocean acidification on food webs and ecosystems. A number of regions, which generate ecological goods and services of particular importance to human societies, are thought to be particularly vulnerable to ocean acidification including high latitudes, deep oceans, upwelling regions and coral reef ecosystems, however few studies are as yet available from these regions.

The global scale of ocean acidification means that the scientific research community must work together to address knowledge gaps. Careful coordination of knowledge requirements with the future research plans of the scientific community will help to meet the research requirements for open-ocean ecosystems, and enhance sampling in currently under-represented ecosystems. Important networks already exist which seek to coordinate international research efforts, synthesise available knowledge, and enable inter-comparison of scientific data.

The risks posed to global environmental, financial, and social structures necessitate consideration of this issue in a variety of policy arenas, and require global agreements and action. While ocean acidification has been recognized as an important emerging issue within the context of the UN Convention on Biological Diversity (CBD), with the potential to undermine achievement of the Convention's mandate, this complex issue has not achieved 'pull through' to other international Conventions and policy processes that its nature might warrant. Furthermore, outside of the scientific community, the ocean acidification issue has not been communicated in a manner to warrant significant action by impacted sectors and stakeholders.

Mechanisms are required to assist policy makers, governments, organisations and wider society to take into account the emerging knowledge and experiences stemming from the monitoring and assessment of ocean acidification impacts on marine and coastal biodiversity globally, and to ensure that the most up-to-date information underpins developing policy to overcome the threats posed by ocean acidification to human society. The forthcoming CBD expert meeting on this issue, to be held in Montreal, Canada, from 19 to 20 October 2011, will thus seek to identify and establish such mechanisms in order to mainstream ocean acidification issues within the context of the Convention and its implementation at the national, regional and global levels.

Background and Introduction

Over the past 250 years, atmospheric carbon dioxide (CO_2) levels have increased by nearly 40% from a preindustrial value of approximately 280 ppm (parts per million) to 391 ppm in 2011 (Conway and Tans, 2011)[1]. This rate of increase is at least an order of magnitude faster than has occurred for millions of years (Doney and Schimel, 2007), and it is suggested that the current atmospheric CO_2 concentration is higher than experienced on Earth for the past 800,000 years (Lűthi et al., 2008).

The surface ocean plays a critical role in the global carbon cycle absorbing nearly one third of the CO_2 emitted to the atmosphere from the burning of fossil fuels, deforestation, and other human activities (Sabine and Feely, 2007; Sabine et al., 2004). Through time as more and more anthropogenic CO_2 has been emitted into the atmosphere the ocean has absorbed greater amounts of CO_2. However, estimates of the ocean carbon uptake rate suggest that the ocean is not keeping pace with the CO_2 emissions growth rate (Sabine and Tanhua, 2010). This oceanic uptake of CO_2 has resulted in changes to the chemical balance of seawater (which is naturally slightly alkaline) and a reduction in the pH termed "ocean acidification" (Doney et al., 2009).

The gradual process of ocean acidification has long been recognized (Broecker and Takahashi, 1966; Bacastow and Keeling, 1973; Feely et al., 1988), but the ecological implications of such chemical changes have only recently been examined (NOAA, 2010). Ocean acidification has the potential to affect the biodiversity and function of a variety of marine ecosystems, and there is growing concern that, in concert with the effects of other human activities, ocean acidification will have important consequences for resources and systems that are important to society (Barry et al., 2011). The risks posed to global environmental, financial, and social structures necessitate consideration of this issue in a variety of policy arenas (Gattuso and Hansson, 2011), and require global agreements and action (Turley and Boot, 2011). The broader implications of ocean acidification to fisheries, aquaculture, and other services deriving from the efficient function of marine ecosystems are not yet well understood, and policy makers, scientists and practitioners need to work together to ensure the most up-to-date information underpins developing policy to overcome the threats posed to human society (Turley and Boot, 2011).

Ocean acidification has been recognized as an important emerging issue within the context of the UN Convention on Biological Diversity (CBD) with the potential to undermine the core principles upon which the Convention is founded. It is anticipated that ocean acidification will make it more challenging to implement the marine and coastal Programme of Work, and to comply with the Addis Ababa principles for sustainable use, which seek to maintain or restore biodiversity to ensure that ecosystems can sustain ecological services on which both biodiversity and people depend (SCBD, 2004).

In response to decision IX/20 (marine and coastal biodiversity), the Secretariat of the Convention on Biological Diversity compiled a comprehensive review of existing literature and scientific information on the observed and predicted impacts of ocean acidification on marine biodiversity (SCBD, 2009). The synthesis was made available for consideration by the Subsidiary Body on Scientific and Technical and Technological

[1] Global monthly mean atmospheric CO_2 concentrations averaged over marine surface sites recorded as ~391ppm in April 2011. This figure is preliminary pending recalibration.

Advice (SBSTTA), at its fourteenth meeting, and used to inform discussions on the treatment of ocean acidification within the context of the marine and coastal Programme of Work at the 10th meeting of the Conference of Parties in 2010.

In its subsequent decision X/29 (marine and coastal biodiversity), the Conference of Parties to the CBD *"…requests the Executive Secretary to develop, in collaboration with the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization (IOC/UNESCO), the Food and Agriculture Organization of the United Nations (FAO), the Secretariat of the United Nations Framework Convention of Climate Change (UNFCCC), the World Conservation Monitoring Centre of the United Nations Environment Programme (UNEP-WCMC), the International Coral Reef Initiative (ICRI), Ramsar Convention, Antarctic Treaty, the Arctic Council, and other relevant organisations and scientific groups, subject to the availability of financial resources, a series of joint expert review processes to monitor and assess the impacts of ocean acidification on marine and coastal biodiversity and widely disseminate the results of this assessment in order to raise awareness of Parties, other Governments and organisations. Given the relationship between atmospheric carbon dioxide concentration and ocean acidification, the Executive Secretary was also requested to transmit the results of these assessments to the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC)*" (CBD, 2010).

The expert review process will seek to identify and establish appropriate mechanisms to better integrate ocean acidification concerns into the CBD and its implementation at the national, regional and global levels, and will enable exploration of relevant policy options. These mechanisms should assist Parties, other governments and organisations to take into account the emerging knowledge on ocean acidification, and ensure that lessons learned from collective experiences and results, stemming from the monitoring and assessment of ocean acidification impacts on marine and coastal biodiversity, are made widely and rapidly available to improve mutual understanding of ocean acidification, the overall practices and methodologies used, and to facilitate international cooperation.

Objectives of the background document

This background document was prepared by the CBD Secretariat in collaboration with Intergovernmental Oceanographic Commission-UNESCO, in order to inform the forthcoming CBD Expert Meeting to Develop a Series of Joint Expert Review Processes to Monitor and Assess the Impacts of Ocean Acidification on Marine and Coastal Biodiversity, to be held in Montreal, Canada, from 19 to 20 October 2011, pursuant to decision X/29 (paragraph 66). It presents an overview of the status of knowledge of the impacts of ocean acidification on marine and coastal biodiversity, and summarizes scientific and technical information gaps and needs, as well as policy and communication perspectives. Furthermore, possible elements and approaches for considering the development of a series of joint expert review processes are proposed. The research for this report was conducted with the kind financial support from the Government of Spain.

In view of the existing CBD scientific synthesis on the impacts of ocean acidification, this background document aims to summarize key messages, and provide an update in terms of new knowledge of the impacts of ocean acidification on marine biodiversity. For a detailed synthesis of the observed and predicted impacts to marine and coastal biodiversity please refer to the CBD Technical Series 46.[2]

[2] available at http://www.cbd.int/doc/publications/cbd-ts-46-en.pdf

Status of Ocean Acidification Science

The technical summary of the Intergovernmental Panel on Climate Change (IPCC) 4th Assessment Report produced in 2007 concluded, "…*Ocean acidification is an emerging issue with potential for major impacts in coastal areas, but there is little understanding of the details*". The report indicates that ocean acidification is an urgent topic for further research, especially programmes of observation and measurement (Parry et al., 2007).

Since the publication of the 4th Assessment Report, ocean acidification research has advanced rapidly. The launch of several national and international research projects has led to a steep increase in attention from the scientific community, policy makers, and the media (Gattuso and Hansson, 2011).

Key information extracted from a bibliographic database of 739 articles (from 1906 to 2010) by Gattuso et al., 2011, confirms a sharp increase in the number of publications considering ocean acidification (with more than 74% of those reviewed published after 2004), and reveals the following trends:

- While the physio-chemical pathways and reactions of CO_2 as it dissolves in seawater are known with a high degree of confidence (Doney et al., 2009), the magnitude of biological and ecological effects are much less certain (Gattuso et al., 2011);
- In view of the relatively solid knowledge that already exists on the chemical aspects of ocean acidification, a large amount of the work in recent years has focused on the biological consequences of ocean acidification for marine organisms (65% of the total number of articles in the database);
- Calcifying and photosynthesising groups of organisms (e.g. phytoplankton, corals, macroalgae, molluscs) have been most comprehensively studied given that processes such as primary production, growth and calcification are directly affected by increasing CO_2 concentrations in seawater;
- Studies of the more subtle effects of ocean acidification for other organisms, for example in terms of performance and reproduction, have been limited until very recently;
- Modelling studies have largely focused on global models (65%) rather than regional models (23%) (Useful for the interpretation of socio-economic impacts), and only five studies modelled a community response to ocean acidification;
- Study sites in the North Atlantic, North Pacific, South Pacific and the Mediterranean have been investigated to a larger extent than the Indian, South Atlantic, Arctic and Southern Oceans and the Baltic, Red and Black Seas. The number of studies of polar-regions is relatively low (Arctic (5%), Southern Oceans (7%)), despite the recognised sensitivity of these areas to ocean acidification; and
- The majority of studies reporting new results were conducted in the laboratory (67%), with far fewer larger-scale field studies (mesocosm), which enable simulation of future ocean pH conditions, under close-to-natural conditions.

These findings provide valuable insight into the areas, organisms and processes that should be considered to a greater extent in the future to increase the overall understanding of ocean acidification (discussed in latter sections) (Gattuso et al., 2011).

Manipulative experiments have been performed to assess the influence of increasing CO_2 and decreasing pH on the physiology of organisms. Many early experiments considered single species responses, the results of which are not easily extrapolated to natural systems (Gattuso et al., 2011). However, recent developments in benthic and pelagic mesocosm experimental observation technology have helped to close the gap between small-scale laboratory experiments and field observations (Widdicombe et al., 2009). Large-scale (60,000 litres) mesocosm technology was tested for the first time in the Baltic Sea in 2009 as part of the European Project on Ocean Acidification (EPOCA). A comprehensive sampling programme using this technology, coordinated by the Leibniz Institute of Marine Sciences in Germany (IFM-GEOMAR), has since been conducted in Norway supporting the elucidation of community responses, and validation and up-scaling of single species responses in vulnerable high latitudes (Orr et al., 2009). Established collaborations among on going programmes such as the EPOCA, UK Ocean Acidification Research Programme (UKOA), Biological Impacts of Ocean Acidification (BioAcid), Mediterranean Sea Acidification in a changing climate (MedSeA) and the NOAA Ocean Acidification Programme will enable the continuation of large-scale mesocosm experimentation.

The study of sites with naturally elevated concentrations of CO_2 provide opportunities to observe and advance the understanding of ocean acidification at the ecosystem and *in situ* species level, and can be examined to provide further information on adaptation mechanisms in low pH environments (Hall-Spencer et al., 2008). There are several areas in the world's oceans where volcanic processes cause CO_2 to vent from submarine sediments in relatively shallow waters. In these areas, CO_2 reacts with the seawater, causing pH and chemistry changes. One such coastal vent area, off the island of Ischia, Italy, has provided critical insights into changes in biological community diversity (Hall-Spencer and Rauer, 2009). Detailed studies are also currently underway in Papua New Guinea (Milne Bay) to understand the biodiversity impacts for warm water coral reefs occurring in a naturally acidified location (Fabricius et al., 2011), with other sites being identified for further study (e.g. Indonesia, Japan).

A global ocean carbon observatory network of repeat hydrographic surveys (e.g. Joint Global Ocean Flux Study, Ocean Atmosphere Carbon Exchange Study) time-series data measurements (e.g. Hawai'i Ocean Time Series station, ALOHA), and ship based surface observations in the Atlantic, Pacific and Indian Oceans has provided a solid foundation for understanding recent changes in the carbonate chemistry of sea-water (NOAA, 2010). These measurements have been used to validate and evaluate outputs from global ocean circulation models, leading to the identification of regions of high vulnerability to ocean acidification, such as the Southern Ocean and the subarctic Pacific (Orr et al., 2005; Cao and Caldeira, 2008), and generating critical projections of future changes (Gattuso and Hansson, 2011). Paleo-oceanographic tracers have also enabled the expansion of instrumental record back in time to explore past carbon cycle perturbations and establish the long-term response of marine organisms to changing conditions (Gattuso and Hansson, 2011).

The global scale of ocean acidification means that the scientific research community must work together to address knowledge gaps. Important international networks exist, which seek to coordinate international research efforts and undertake synthesis of available knowledge. Amongst others these include the International Geosphere-Biosphere Programme (IGBP), the Scientific Committee on Oceanic Research (SCOR), UNESCO's Intergovernmental Oceanographic Commission (IOC), Surface Ocean - Lower Atmosphere Study (SOLAS), Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) and the International Ocean Acidification Reference Users Group (IOARUG). Coordination within Europe is well underway, and increasing in North

America through the establishment of an Interagency Working Group on Ocean Acidification (IWGOA) to link ocean acidification research activities within the Federal agencies, including the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF). However, it is necessary to better integrate European and North American activities with the wider global effort on ocean acidification research (e.g. Japan, Korea, Australia and China) (ESF, 2009). Furthermore, it will be important to facilitate participation of developing country scientists, as well as other key stakeholders (e.g. policymakers, fishermen, etc.), in the field of ocean acidification research as it evolves.

Initiative Name	Geographic Focus	Scale	Value	Research Emphasis	Duration	Supporters
European Project on Ocean Acidification (EPOCA)	Europe	Regional	EUR6.5 million		2008-2011	European Union
Biological Impacts of Ocean Acidification (BioAcid)	Germany	National	EUR8.9 million (Phase 1)	To understand the effects of ocean acidification on marine organisms and their habitats; To establish the underlying mechanisms of responses and adaptations at the population and community levels; To examine how these are modulated by other environmental stressors	2009-2012	
UK Ocean Acidification Programme (UKOA)	United Kingdom	National	GBP 12 million	To reduce uncertainties in predictions of carbonate chemistry changes and their effects on marine biogeochemistry; To understand the responses to ocean acidification by marine organisms, biodiversity and ecosystems and to improve understanding of resistance or susceptibility; To provide data and effective advice to policy makers and managers on the size and timescale of risks	2009-2014	National Environment Research Council (NERC), UK Government (DEFRA, DECC)
Ocean Carbon and Biogeochemistry (OCB)	USA	National		To study the role of the ocean in the global carbon cycle, in the face of environmental variability and change. Ocean acidification is an identified research priority.		National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA)
Federal Ocean Acidification Research and Monitoring (FOARAM) Act	USA	National	~USD 30 million per year	Interagency committee to oversee planning, establishment and coordinated implementation of a plan to improve understanding of the role of increased ocean acidification on marine ecosystems. Programme within NOAA.	Launched in 2011	US Congress
Mediterranean Sea Acidification	Mediterranean	Regional (10 countrie	EUR 6 million	Assess uncertainties, risks and thresholds related to Mediterranean acidification	2011-2014	European Union (EUR3.5 million)

under Changing Climate Project (MedSeA)		s)		at organisms, ecosystem and economical scales. It will convey knowledge to a wide audience of reference users, and suggest policy measures for adaptation and mitigation.		
Acidification Impact on Calcifiers (AICAL)	Japan	National		Inter-agency collaboration to examine effects of ocean acidification on a wide range of marine organisms using precise pCO_2 control systems from temperate to sub tropical areas.	2008-2012	Global Environment Facility, Government of Japan - Ministry of Environment
Australian Antarctic Program	Australia	National		Vulnerability of Antarctic marine benthos to increased temperatures and ocean acidification associated with climate change.	2009 - 2012	
Hot Spot Ecosystem Research and Man's Impact on European Seas	Europe	Regional	EUR 8 million	Exploring deep sea environments including impacts of ocean acidification and increasing CO2 concentrations on deep water ecosystems.	2009-2012	European Union
SOLAS		Global (75 countries)		To achieve quantitative understanding of the key biogeochemical-physical interactions and feedbacks between the ocean and atmosphere, and of how this coupled system affects and is affected by climate and environmental change.		SCOR, IGBP, WCRP, ICACGP
National Science Foundation	USA	National	USD 15 million	Support for research on ocean acidification (chemistry, implications for biochemical and physiological processes, impacts on ecosystem structure and function) including development of interdisciplinary partnerships and capacity building.	Launched in 2010	
CHOICE-C	China	National	RMB 34 million	Study of high CO_2 and ocean acidification issues in Chinese marginal seas.	2010-2015	Ministry of Science and Technology, National Science Foundation of China
Arctic Tipping Points	Europe	Regional		To identify elements of the Arctic marine ecosystem likely to show abrupt changes in response to climate change, and establish the levels of the corresponding climate drivers including regime shift in those tipping elements.		European Union

Table 1: Major National and International Ocean Acidification Research Initiatives

*This is not an exhaustive list and many more small-scale projects and activities are underway that will likely be very important in studying the specific effects of ocean acidification. The major international projects form a framework within which national/regional projects, with their own priorities can create synergies.

What do we know?

Global status and trends of ocean acidification and impacts on critical ecosystems

The surface waters of the oceans, in present day, are naturally slightly alkaline, with an overall mean pH of ~8.1 on the seawater scale (Feely et al., 2009). During the past 250 years the average sea surface pH has decreased by about 0.1pH units, equivalent to a 30% increase in hydrogen ions and amounts to a considerable acidification of the oceans (The Royal Society, 2005). There is very high certainty among the scientific community that the observed change in seawater chemistry is due to rising atmospheric CO_2, and that human activities are the root cause (OARUG, 2010).

Atmospheric CO_2 concentrations are predicted to increase by 0.5 – 1% per year throughout the 21st century (Meehl et al., 2007). Increasing prevalence of ocean acidification has been linked empirically to the accelerating trend in world CO_2 emissions, albeit with a time lag as the CO_2 is absorbed into the oceans, and by 2100 it is predicted that ocean acidity could increase by 150% (Orr et al., 2005). It can be stated with a very high level of confidence that the magnitude of future ocean acidification depends on the emission pathways that are being considered in global climate change negotiations and debates. This is largely based on the current knowledge and understanding of the complex but predictable marine carbonate chemistry reactions and cycles, and robust evidence from modelling, time-series stations and repeat measurements (Gattuso et al., 2011).

Generally the surface waters of the contemporary global oceans are super-saturated with carbonate minerals favouring the formation of shells and skeletons in calcifying organisms (e.g. zooplankton, corals, molluscs, echinoderms and crustaceans). However, as CO_2 driven ocean acidity increases, carbonate ions are removed from the system. Seawater that is under-saturated with carbonate minerals can become corrosive and, in the absence of protective mechanisms, the shells of calcifying organisms increasingly prone to dissolution (Feely et al, 1988). Predicting the impacts on marine calcifiers as a whole is difficult since the major groups carry out calcification via different routes and mechanisms (Turley et al., 2010). Despite some perturbation experiments reporting no effect or a positive effect of ocean acidification on the rate of calcification for a few organisms, overall there is high level of confidence that ocean acidification will adversely effect calcification rates in shell forming animals (Gattuso et al., 2011), impacting shell production and making the process more physiologically costly (NOAA, 2010).

While there has been impressive development in the field of ocean acidification research in the past few years, questions remain about its biological and biogeochemical consequences, and the accurate determination of sub critical levels or "tipping points' for global marine species, ecosystems and services, which are known with only a moderate level of confidence (Gattuso and Hannson, 2011). A recent meta-analysis of biological responses to ocean acidification among populations of a single species as well as multiple species assemblages revealed an overall significant negative effect on survival, calcification, growth and reproduction, suggesting predicted ocean acidification conditions will have negative consequences for many marine organisms by the end of the century (Kroeker et al., 2011).

There is increasing concern that ocean acidification could affect the functioning of marine ecosystems; however the mechanisms by which population declines will occur have not been identified, especially for non-calcifying species such as fishes. Results of recent experimentations show that CO_2 concentrations, as predicted to occur by the end of the century, may have dramatic effects on the behaviour of fish larvae, with highly significant consequences for population replenishment and sustainability (Munday et al., 2011). Furthermore, shifts in the composition or distribution of plankton communities, resulting from decreased fitness or survivorship of calcifying organisms (Guinotte and Fabry, 2009), may reduce survival in the early life stages of some fish species.

While ocean acidification is a global issue, regional and seasonal influences, combined with biological, chemical and physical factors (e.g. carbonate chemistry, biological productivity, the effects of temperature on CO_2 solubility) imply that the impacts of ocean acidification will vary in intensity and timing (Royal Society, 2005). There are areas which already naturally experience lower pH and carbonate ion concentrations than the global average, and are therefore more sensitive to ocean acidification including:

High Latitude Regions

High latitude regions have naturally low levels of carbonate minerals and owing to the increased solubility of CO_2 at cold temperatures, hold more CO_2 and are more acidic than warmer waters (Guinotte and Fabry, 2008). Global models project that the surface waters of the high latitudes will become persistently under-saturated with respect to aragonite as early as 2050, given current emission rates (Fabry et al., 2009). Particularly fast rates of change are expected in the Arctic Ocean with 10% of its waters projected to be undersaturated with aragonite within the next decade (Orr et al., 2008). Seasonal fluctuations in carbonate saturation in the Southern Ocean suggest that aragonite under-saturation of the surface waters could occur as early as 2030 during the winter months (McNeil and Matear, 2008); a situation that has probably not occurred in at least the last 400,000 years (Orr et al., 2005). Furthermore, recent results indicate that aragonite under-saturation in surface and shallow sub surface waters of some areas of northern polar seas has already been observed (Fabry et al., 2009).

Calcified marine organisms, including swimming snails (pterpods), sea urchins, molluscs and coralline algae make up significant components of high latitude ecosystems (Fabry, 2009). Immersion of shelled pteropods in high-CO_2, low carbonate waters is known to weaken their aragonite shells (Orr et al., 2005) and is expected to reduce their survival and productivity (Comeau et al., 2009). The combined impacts of rising partial pressure of CO_2 (pCO_2) and elevated temperatures, as projected for this century, were shown to significantly increase mortality in juvenile polar pteropod *Limacina helicina* (Lischka et al., 2011). If high-latitude surface waters become increasingly more acidic as predicted, pteropods could eventually be eliminated from some regions, with consequences to food web dynamics and other ecosystem processes (Fabry et al., 2008; Barry et al., 2011).

Deep-Sea Environments

Deep-sea ecosystems may experience some of the most profound changes in biodiversity and ecosystem function in response to ocean acidification. The progressive shallowing (shoaling) of the aragonite and calcite saturation boundaries (above which shell production is favoured, and below which dissolution may occur) will cause shifts in habitat quality for deep-sea calcifiers (Barry et al., 2011). The aragonite saturation horizon in the deep Arctic Ocean is currently at 2,500m, while the horizon depth in the

Iceland Sea is 1,750m and rising at 4m yr^{-1} (Olafsson et al., 2009). Due to the local elevation of the sea floor in the Iceland Sea a further 800km^2 of sea floor, previously bathed in saturated waters, is exposed to under-saturated conditions each year (Olafsson et al., 2009).

Indeed, important cold-water coral communities will likely be the first casualties of increasing ocean acidity, with the deepest communities in each ocean first to experience a shift from saturated to unsaturated conditions (Doney et al., 2009). According to predictions, 70% of known cold-water coral ecosystems could experience corrosive water conditions by the end of the century, although some may experience aragonite under-saturation as early as 2020 (Guinotte et al., 2006). The predicted decline in carbonate saturation levels will severely affect the continued provision of services from these ecosystems such as shelter and food for hundreds of associated species, including commercial fish and shellfish.

Upwelling Regions

Wind-driven, seasonal upwelling of subsurface waters at the equator and coastal margins brings CO_2-enriched waters onto the shelf and, in some instances, into the surface ocean. This water contains a high level of CO_2 resulting from natural respiration processes in the subsurface layers and is also significantly contaminated with anthropogenic CO_2 (Feely et al., 2008).

Along the west coast of North America seasonal upwelling processes enhance the advancement of corrosive deep water into broad regions of the continental shelf (Feely et al., 2008). While this is a natural phenomenon in the region, the oceanic uptake of anthropogenic CO_2 has increased the area covered by under-saturated water and the potential threat of these acidified waters to many of the calcifying species that live along the coast (Feely, 2009).

In 2008, observations indicated that bivalve shellfish hatcheries on the west coast were experiencing significant declines in production as a result of low pH waters (Feely et al., 2008). A NOAA-led interagency and regional effort has provided real time monitoring data as part of an early warning system for shellfish hatcheries, signalling the approach of cold, acidified seawater in advance of its arrival in the sensitive coastal waters where larvae are cultivated, leading to efficient industry adaptations and partial restoration of productivity (See Box 1) (NOAA, 2011).

Because seasonal upwelling is a common phenomenon in many coastal regions, this process may be affecting coastal ecosystems in other locations as well (Feely et al., 2010). Some of the world's most productive fisheries are associated with coastal zones in temperate latitudes, suggesting that the impacts on marine food webs caused by ocean acidification could be severe and a more urgent issue than previously thought.

Estuarine Ecosystems

Coastal and estuarine ecosystems are highly biologically productive yet are more prone to changes in pH than the open ocean due to their shallower depth, lower salinity and lower alkalinity (Miller et al., 2009). These systems provide significant measurable ecosystem services including support for commercial and recreational fisheries, nursery grounds for fish and invertebrate species, water purification, flood and storm surge protection and human recreation (Miller et al., 2009).

Local studies in the Kennebec River plume in the Gulf of Maine and the Manning River estuary in New South Wales, Australia illustrate that fresh water inputs, pollutants, and soil erosion can acidify coastal waters at substantially higher rates than atmospheric CO_2 alone (Kelly et al., 2011).

Comparatively little research, including socio-economic studies, has been undertaken regarding the implications of ocean acidification on commercial fin-fish and shellfish (Fabry et al., 2008; Turley et al., 2009), both of which are of direct interest for human food provision. Although, one recent economic study, based on an assumption of constant demand for shellfish products, estimates that the global and regional economic costs of production loss of molluscs due to ocean acidification could amount to between ~6 - 100 billion USD by the end of the century under current emission scenario (Narita et al., 2011).

Tropical Regions

In tropical regions adverse changes in carbonate ion availability as a result of decreasing pH are likely to be exacerbated by the lack of mixing between the warm, shallow, CO_2-enhanced surface layers and the buffering effects of cool, deep ocean waters (Veron, 2008). In localised areas, such as the eastern tropical Pacific (ETP), surface waters already have lower pH and lower carbonate saturation relative to other tropical marine areas due to upwelling processes that mix CO_2 enriched, deep waters into the surface layers. Concurrently, ETP reef frameworks are very poorly cemented and only held in place by a thin envelope of encrusting organisms. This makes them highly susceptible to bioerosion (Manzello et al., 2008).

Although surface water of tropical areas are not expected to become under-saturated with respect to aragonite, carbonate coral reefs do not exist in waters with carbonate-ion concentrations of less than 200 µmol kg-1[3]. As the world's oceans become less saturated with respect to carbonate minerals over time, corals are expected to build weaker skeletons and experience slower growth rates, which will make it more difficult for corals to retain competitive advantage over other marine organisms (Guinotte et al., 2006, Atkinson and Cuet, 2008). Increasingly brittle coral skeletons are at greater risk of storm damage, and bioerosion, which will reduce the structural complexity of the reef system, reducing habitat quality and diversity alongside the loss of coastal protection functions (Hoegh-Guldberg et al., 2007).

Variability in impacts of observed and predicted impacts

As more results on the sensitivity of organisms and communities to ocean acidification becomes available, the breadth and depth of knowledge of consequences and causes grows. At the same time, the evolving picture becomes blurred by conflicting results (Gattuso et al., 2011).

Some experiments have shown both increasing (Iglesias-Rodriques et al., 2008) and decreasing (Wolf-Gladrow et al., 1999) coccolithophore calcification under elevated CO_2 conditions, even in the same species. Contrary to expectation, a small number of studies have reported enhanced structural calcification in response to increasing CO_2 levels in species of some invertebrates, e.g. juvenile cephalopod mollusc (Gutowska et al., 2008), crustaceans (Ries et al., 2009), and juvenile fish (Checkley et al., 2009). Furthermore, contrasting results have been obtained in terms of growth rates, nutrient uptake ratios,

[3] Currently, carbonate ion concentrations are ~210µmol kg^{-1}, lower than at any time during the past 420,000 years (Hoegh-Guldberg et al, 2007).

and carbon fixation by different groups of phytoplankton under high CO_2 conditions (Riebesell et al., 2007, Rost et al., 2008).

While part of this may simply reflect species-specific differences or the plasticity of organisms in responding to environmental stressors, part of the discrepancy may result from a lack of standardised protocols, or misinterpretation of the data (Gattuso et al., 2011). To facilitate greater comparability of experimental data and provide guidance to the research community in this rapidly growing field, a Guide to Best Practices in Ocean Acidification Research and Data Reporting has been prepared (Riebesell et al., 2009).

Sensitivity, acclimation and adaptation

Evidence suggests that the responses of marine organisms and ecosystems will be variable and complex, impacting developmental and adult phases differently across species depending on genetics, pre-adaptive mechanisms, and synergistic environmental factors (Cummings et al., 2011). Early life stages may be particularly sensitive to acidification. For example, ocean acidification negatively affects sea urchin reproduction by reducing sperm motility and swimming ability, lowering fertilization success, and impeding embryo and larval development (Havenhand et al., 2008).

Highly mobile organisms with well developed respiratory and circulatory systems and ion-regulatory mechanisms poses a certain level of pre-adaption for many of the stresses related to ocean acidification and may be more resilient (e.g. teleost fish cephalopods and many brachyuran crustaceans) (Melzner et al., 2009a; Kroeker et al., 2010). A study of the active cephalopod mollusc *Sepia officinalis* demonstrated that this invertebrate is capable of not only maintaining calcification, but also growth rates and metabolism when exposed to elevated pCO_2 (Gutowska et al., 2008). Recent findings from the long-term acclimation of Atlantic cod (*Gadus morhua*) also indicate negligible impact of increased pCO_2 concentrations on maximum swimming performance and metabolism (Melzner et al., 2009b). Little information is available at present on early developmental stages for seemingly tolerant organisms, which are thought to be particularly vulnerable (Melzner et al., 2009a).

Taxa with weaker control over internal fluid chemistry are considered to be at greater risk from ocean acidification (e.g. brachiopods and echinoderms) (Barry et al., 2011). For example, Echinoderms are conspicuously absent from habitats with naturally high CO_2 levels such as shallow CO_2 vents in Ischia off the coast of Italy suggesting that they may be less tolerant of low-pH waters than many groups (Hall-Spencer, 2008).

Marine calcifiers depositing hard parts that contain significant concentrations of magnesium (e.g. Coralline red algae — the primary cementer that makes coral reef formation possible) are also likely to exhibit greater sensitivity to increasing ocean acidification. These organisms exist under conditions which are already more corrosive to their shells and skeletons than organisms depositing less soluble mineral phases (Andersson et al., 2008).

The capacity of calcifying marine organisms to adapt to progressively acidified oceans is an important but unresolved question, but may be a function of species generation time, which suggests that long-lived species, such as warm- and cold-water corals, will be less able to respond. Shorter generation times may afford increased opportunities for micro-evolutionary adaptation (Royal Society, 2005). Experiments with calcifying phytoplankton indicate no adaptation to high CO_2 after even after 150 generations (Müller et al., 2008). Although few experiments have been conducted for long enough to indicate whether organisms will be able to genetically adapt to the changes.

Adaptation potential can be deduced from *in situ* observations at natural CO_2 venting sites, where benthic marine communities have experienced high pCO_2 and low pH conditions for several centuries or millennia. While this approach provides some valuable information on the potential range of adaptive responses at the organism, community and ecosystem levels the extrapolation of the observed responses to future ocean acidification is complicated. Currently the level of evidence that some species will adapt is low (Gattuso et al., 2011).

Migration by individual organisms or populations faced with ocean acidification may be possible via successive range shifts though generations, but the global nature of ocean acidification coupled with range limitation imposed by other parameters (e.g. temperature) may limit this option (Barry et al., 2011).

What more do we need to know/where do we focus next?

The great majority of the growing evidence from field work, experiments, modelling, and the geological record indicates that the consequences of ocean acidification for the future could be very serious, but there are still substantial knowledge gaps and uncertainties, particularly in terms of the biogeochemical impacts and impacts of ocean acidification on food webs and ecosystems. This is in part due to a lack of research in the area but also due to increasing uncertainty with the complexity of marine systems (Turley and Boot, 2011).

The scientific community has limited resources and time (given the rapid rates of change) to understand what the consequences of ocean acidification on the future ocean will be and to inform solutions for managing predicted impacts (Dupont and Thorndyke, 2009). The following section outlines limitations recognised by the scientific community in research conducted to date and presents indicated priorities for future studies to respond to these research limitations.

Consistent methodologies and best practices: A lack of coordination or agreement on experimental methods, protocols and data reporting has limited the comparison of experimental results (Orr et al., 2009). Best practice guidance has been developed to avoid pitfalls and confusion in the literature (Gattuso et al., 2011), however there is a need to build on this initial investment. It will be important to develop, test and adopt internationally agreed, standardised protocols for observational and experimental approaches, carbonate chemistry manipulations and measurements, and data reporting to achieve highest possible data quality and enable global assessment (Gattuso and Laffoley, 2011).

Duration of experiments: Understanding of the sensitivity of marine organisms to ocean acidification is almost entirely based on short-term perturbation experiments, lasting between a few hours and a few weeks (Gattuso et al., 2011). The results of such studies provide valuable insights into the phenotypic response of test organisms and communities to ocean acidification, however are generally shorter than the generation time of the organism. Experiments which take account of generation time, and if possible several generations, provide opportunity to explore scope for evolutionary adaptation on ecological timescales (Dupont and Thorndyke, 2009). Due to the important role that adaptive processes may have on the response of the biota to ocean acidification it is crucial to make the best use of all available approaches for addressing this critical issue (Gattuso et al., 2011). This should include the observation of naturally acidified locations and an improved understanding of previous ocean acidification events in Earth's history, which can provide useful insights into extinctions or adaptation strategies.

Interactions with other stressors: The onset of changes in biodiversity and ecosystem function due to ocean acidification may be difficult to detect amidst the variability associated with other human and non-human factors, thus preventing their effective observation. The greatest impacts are expected to occur as acidification intensifies through this century (Barry et al., 2011). In order to accurately predict the consequences of ocean acidification for marine biodiversity and ecosystems, the ecological effects must be considered in relation to other environmental changes associated with global climate change, and the interplay between the complex biological and chemical feedbacks (Royal Society, 2005). Experiments on molluscs (Parker et al., 2009) and echinoderms (Byrne and Davis, 2008; Dupont and Thorndyke, 2008; Wren et al., 2008) demonstrate that some negative impacts of ocean acidification can only be observed when combined with increasing temperature stress as expected for the end of the century. Future studies should therefore expand to test for synergistic effects of environmental stressors in concert with ocean acidification (Fabry et al., 2009). Results obtained in isolation from other relevant influences should also be verified under more realistic conditions with multiple interacting variables (Barry et al., 2011).

Life History Stages: Most studies so far have focused only on selected phases of test organisms' life cycles. An individual may experience very different environmental conditions at different stages during its life cycle and its potential to adapt to stress is likely to vary over different developmental phases (Gattuso et al., 2011). Future research should endeavour to cover all life history stages – eggs, larvae, juveniles, adults and back to eggs.

Community level responses: Most research concerning the biological effects of ocean acidification has focused on aspects of the performance and survival of individual species during short term studies, assuming that individual performance will influence ecosystem function. By their nature, controlled experimental studies are limited in both space and time, and thus may not capture important processes (e.g. acclimatization and adaptation, multispecies biological interactions, chronic low level impacts) that can ultimately play large roles in the response of marine systems to ocean acidification. The scaling up from individual to ecosystem level effects is the most challenging goal for research on the potential impacts of ocean acidification (Barry et al., 2011), and the expansion of community-level investigations is required.

Food Webs: Despite major uncertainties, the research community must prioritize finding ways to scale-up understanding of biological responses of individual organisms to provide meaningful predictions of how ocean acidification will affect food webs, fisheries, and tourism (Orr et al., 2009). Joint international ecosystem studies are needed focusing on the impacts of ocean acidification on key energy flow linkages including primary producers, grazers, intermediate prey and top predators (Gattuso and Laffoley, 2011).

The Human Dimension: A clear gap in the understanding of ocean acidification is the lack of projections relating to the socio-economic impacts of ocean acidification for human societies. This is of critical importance to mitigate further ocean acidification and to develop appropriate adaptation strategies. Social science and economic research in particular must become an integral part of the scientific research agenda in order to determine the vulnerability to ocean acidification of human communities dependent on marine goods and services, requiring multi-disciplinary collaboration. In this vein, there is an essential need to establish two-way communication with stakeholders to better understand their problems and questions so that research can be properly designed and information conveyed in a useful manner. Critical stakeholders include fisheries and marine habitat managers, fishermen, community leaders, conservation groups, etc. (ESF, 2009).

Model development: Ocean circulation models that utilise biogeochemical (carbon cycle) parameterizations have been used to assess the past, present and future states of ocean acidification. The coarse resolution of these models has however limited effective representation of processes in coastal and estuarine ecosystems, and the development and testing of higher-resolution biogeochemical models is recommended (NOAA, 2010). Furthermore, to address ocean acidification impacts of organisms, ecosystem models need to be improved to include responses and feedbacks between lower and higher tropic levels of the marine food web, which have implications for ecosystem structure and function (NOAA, 2010). Improved parameterisation and validation of physical-biogeochemical-ecosystem models (with observational data) is required to understand the impacts of ocean acidification in coastal regions and estuarine ecosystems, where significant marine resources are concentrated. Modelling at a scale that is appropriate for socio-economic interpretations will support generation of policy relevant information on the economic and social impacts of ocean acidification (JNCC, 2007).

Research in vulnerable ecosystems: Because surface waters in high latitudes will be the first ocean regions to become persistently undersaturated with respect to aragonite as a result of human activities, polar and sub-polar seas are a bellwether for global ocean acidification. Over the next decades trends of rising temperatures and species invasions coupled with progressive ocean acidification are expected to increasingly influence both planktonic and benthic marine communities of Antarctica and Arctic. The rate and magnitude of these changes underscore the urgent need for increased efforts in ocean acidity research and monitoring in polar and sub polar seas (Fabry et al., 2009). Other vulnerable areas, including estuarine and deep-sea ecosystems should also receive increasing research attention, given the importance of ecological goods and services generated in these areas to human societies.

International Ocean Acidification Observing Network: In order to develop capacity to predict on going and future responses of marine biota, ecosystem processes, biogeochemistry and climate feedbacks to ocean acidification, a coordinated multidisciplinary approach to observation and monitoring is required (Feely et al, 2010). Careful coordination of knowledge requirements with the future research plans of the ocean carbon and biological communities, and expanding the global time-series network with new carbon and pH sensors and moorings where needed, will help meet the research requirements for open-ocean, and enhance sampling in currently under-represented ecosystems such as coastal environments (Figure 1) (Feely et al, 2010). Continued observations (through research cruises, measurements from volunteer ships, national time-series stations) are essential, alongside inter-comparison studies and experimental and observational approaches combining multiple disciplines (Gattuso and Laffoley, 2011).

An International Workshop to Develop an Ocean Acidification Observing Network of Ship Surveys, Moorings, Floats and Gliders, co-sponsored by NOAA, the University of Washington, USA, the International Ocean Carbon Coordination Project (IOCCP), and Global Ocean Observing System (GOOS), is being organized in Seattle, Washington, USA in the late spring of 2012 for a group of 40-50 international scientists and program managers. The principal goals of this international workshop are to: (1) design the components and locations of an international ocean acidification observing network that includes repeat surveys, and measurements on volunteer observing ships, moorings, floats and gliders; (2) identify measurement parameters and performance metrics for each major component of the observing system; and (3) develop strategy for data quality assurance and distribution.

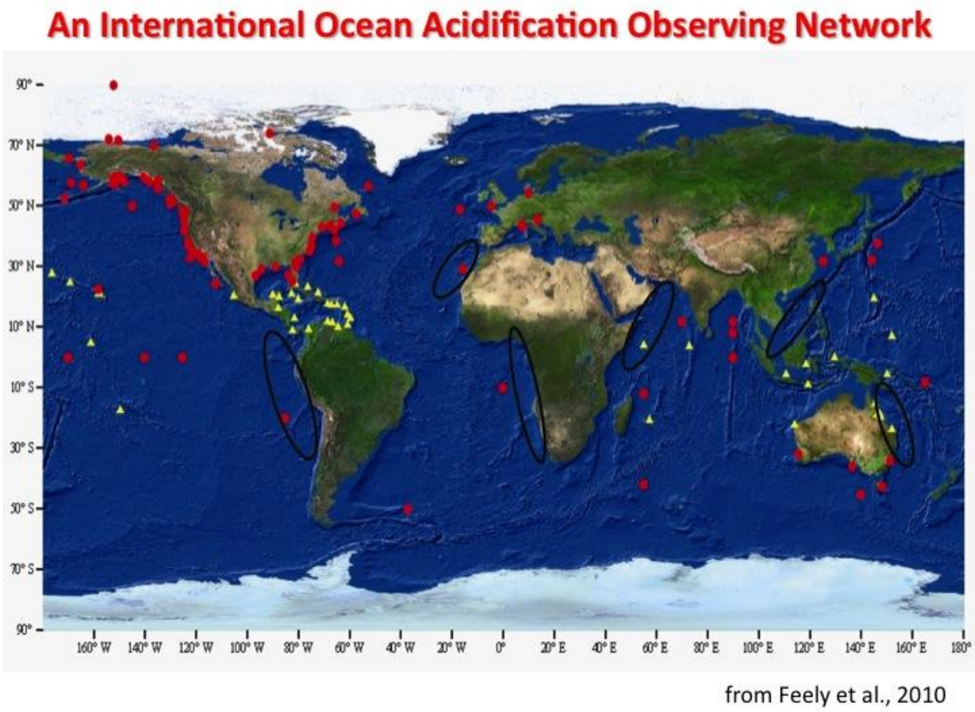

Figure 1: Recommended distribution of time-series sites based on national plans for ocean acidification research and discussions of what is needed by the Ocean Acidification Working Group. Source: Feely et al., 2010.

Figure notes: Red circles represent deployed or planned open-ocean monitoring sites; yellow triangles represent deployed or planned coral reef monitoring sites. Future sites likely to experience seasonal aragonite undersaturation in the near future are indicated by ovals. The entire Arctic Ocean and Southern Ocean are also likely to experience aragonite undersaturation in the near future.

International Collaboration: Effective international research on ocean acidification requires common access to community resources and facilities, which are not typically available to individual research groups. Collaboration can optimize limited resources, highlight common priorities, facilitate greater data and information sharing, and enable exchange of expertise in mesocosm, laboratory manipulations, or particular analytical techniques (Orr et al., 2009). Coordination at the international level will become increasingly important to avoid excessive redundancy, as national research activities emerge worldwide (Gattuso and Laffoley, 2011). There is broad support among a number of national projects as well as by key organisations, including IOC-UNESCO, SCOR, and SOLAS and IMBER, that an *'Ocean Acidification International Coordination Office (OA-ICO)'* should be established to serve the needs of the research community and stakeholders.

Capacity development and awareness raising: Improving capacities in developing countries to recognise and respond to the threats posed by ocean acidification is urgently needed. This should include not only training future scientists but also strengthening capacities of research, scientific, oceanographic, policy and socio-economic institutions in developing countries (UN DESA, 2009). Technical cooperation with and assistance to regional and international institutions with relevant experience is one mechanism to advance this in the near term, which will also support transmission of the latest information on ocean acidification to key stakeholders.

What can we do about OA?

Principle policy solutions

Green House Gas (GHG) Emission Reductions

Ocean acidification is irreversible on short-term timeframes and substantial damage to ocean ecosystems can only be avoided through urgent and rapid reductions in global emissions of CO_2 (IAP, 2009). Even with significant cuts, past emissions of CO_2 already in the atmosphere will continue to contribute to future acidification for many years to come, adding to already observable impacts (Ray, 2011). While efforts to reach a binding agreement at the international level have thus far proved unsuccessful, it is essential that ocean acidification is recognised and integrated into the global CO_2 emission reduction debate.

The United Nations Framework Convention on Climate Change (UNFCCC) calls for the stabilisation of atmospheric greenhouse gas concentrations at levels that "prevent dangerous anthropogenic interference with the climate system", however the Convention does not define what constitutes "dangerous interference" (Cao and Caldeira, 2008). Several international committees and organisations have suggested a target atmospheric CO_2 concentration of 450 ppm as a safe level for a stable Earth (Veron, 2011). However, some model predictions suggest that ocean chemistry will be significantly perturbed even if atmospheric CO_2 can be stabilized at this modest level (Cao and Caldeira, 2008). International and national emission targets must be set at sufficient levels to allow marine ecosystems to adapt naturally to increased acidity and to ensure that marine and coastal food production is not threatened (Harrould-Kolieb and Herr, 2010).

By its very nature, ocean acidification and its causes and effects are cross cutting, and lend themselves to treatment under a variety of international regimes, including the CBD, UNFCCC, and the UN Convention on the Law of the Sea. Cuts in global emissions will require swift implementation of ambitious international agreements complemented by local, regional, and national initiatives that lead the effort to meet this challenge early on (Orr et al., 2009). The current status of policy integration is discussed in latter sections.

Managing for Ecosystem Resilience

In the absence of significant reductions in emissions, acidification will continue, requiring adaptation based measures. While mitigation involves a global commitment, adaptation actions can be adopted at the local, national and international levels (Ray, 2011) as part of broader efforts to preserve and maintain marine ecosystems (UN-DESA, 2009). Despite a widely held perception that acidification cannot be addressed at such scales, local, municipal or national laws in many countries are already in place to address many stressors that drive or exacerbate acidification conditions (Kelly et al., 2011). Relieving pressure on the resources under stress through the adoption and effective enforcement of policies to enhance the resilience of marine ecosystems - for example reducing overfishing, improving water quality, creating marine protected areas - may have a positive effect on the ability of marine ecosystems to adapt to acidifying conditions (Cooley et al., 2009).

The potential biological, ecological and socio economic effects of acidification are likely to affect nearshore environments most severely, impacting the delivery of critical ecosystem services and costing billions of dollars in lost product and income (Cooley and Doney, 2009). Approaches to manage and reduce additional stressors and build resilience in coastal ecosystems offer potential adaptation measures to limit the vulnerability of ecosystems to the stresses of locally intensified acidification (Kelly et al., 2011), including:

- Effective watershed management to reduce runoff and associated pollutants (including storm water surge prevention, maintaining intact wetlands, improved water treatment facilities)
- Control of coastal erosion to reduce nutrient and sediment loading of water and protect physical integrity of habitats (including increasing vegetation cover, coordination among local and municipal governments for watershed-scale action).
- Land use management through local and regional planning, zoning and permitting to reduce direct and indirect CO_2 emissions, runoff and other threats.
- Reduction of local pollutants through enforcement of existing emissions limits for pollutants.

Furthermore, certain coastal and marine ecosystems such as mangrove forests, saltwater marshlands, seagrass meadows and kelp forests absorb and store atmospheric CO_2 and thereby play a critical role in maintaining the Earth's climate (termed Blue Carbon sinks). Preventing the further loss and degradation of these ecosystems and catalysing their recovery can contribute to offsetting fossil fuel emissions (~3-7% of current emissions in two decades). The effect is suggested to be equivalent to at least 10% of the reductions needed to keep concentrations of CO_2 in the atmosphere below 450 ppm (Nellemann et al., 2009), running contrary to the perception that mitigation and emission reductions represent a cost and not an investment.

The rate of loss of these ecosystems is unclear, but rough estimates calculate that between 0.7% – 2% are lost each year (Murray et al., 2011). Loss and conversion of coastal wetlands typically occurs through draining, dredging, landfill, sediment diversion and hydraulic alteration (Crooks et al., 2011). Conversion for agriculture, aquaculture, and wood harvest are the principle contributors to mangrove loss, while salt marshes are typically drained for either agriculture or salt ponds (Murray et al., 2011). The loss of sea grass beds is primarily driven by water quality degradation and mechanical damage from dredging, trawling and anchoring (Murray et al., 2011). Improved integrated management of the coastal and marine environment is critical to reduce and remove threats, support the robust recovery potential inherent in blue carbon sink communities, and maintain food and livelihood security from the oceans.

Despite its significance and potential for cost effective net emission reductions, blue carbon sinks have largely fallen outside of international and national climate change policies (O'Sullivan et al., 2011).

Integration of Ocean Acidification Considerations into National Biodiversity Strategies and Action Plans (NBSAPs)

Due to its long term and progressive impact on the ocean, ocean acidification has become one of the most critical and pressing issues for marine biodiversity and human societies who depend on healthy marine ecosystems (Harrould-Kolieb and Herr, 2010). Several countries including Australia, Chile, Indonesia, Ireland, Japan, Portugal and the United Kingdom make reference to ocean acidification and its implications for marine ecosystems and fisheries in their national climate change plans and strategies (Harrould-Kolieb and Herr, 2010). However, specific national action plans and strategies to deal with ocean acidification are largely missing. It will be particularly important to ensure the incorporation of emerging scientific knowledge on ocean acidification into national biodiversity strategies and action plans, national and local plans on integrated marine and coastal area management, and the design and management of plans for marine and coastal protected areas.

An action-orientated approach to ocean acidification is needed, alongside guidance for national implementation of related mechanisms and projects. In recognition of the significant degree of uncertainty and the need for immediate broad scale action, policy solutions should be coupled with appropriate research and capacity development components, particularly in the context of developing country parties. The Copenhagen Accord, agreed to by 114 parties in 2009, committed developed countries (responsible for the largest portion of historic CO_2 emissions) to providing financial resources to support adaptation measures in developing countries (UNFCCC, 2010).

Communicating About Ocean Acidification

While ocean acidification, like climate change has moved from a purely scientific subject to one of wider public interest (Veron, 2011) it has not entered the mainstream media to any significant degree. Recent media interest has, albeit sparingly and usually around the latest science being published or a dedicated event (e.g. UNFCCC CoP 15 and 16), begun to introduce the subject of ocean acidification to the public through special feature coverage or op-eds (opposite the editorial page). While some in-roads are being made into mainstream media, ocean acidification is also starting to appear in what might be termed the 'peripheral media' that has primarily focused on denying climate change (e.g. climaterealists.org, Science and Public Policy Institute, etc.). Perversely this may be a good indicator of success that the message is starting to get through and sectors of society are taking notice, but it does underscore the importance of generating sound science that supports the consistent communication of ocean acidification.

Effective communication is one important tool to address cultural norms, as far as CO_2 emissions are concerned, and to encourage the formation of plausible solutions to ocean acidification. To date – outside of the ocean acidification scientific community – the ocean acidification issue has been not been communicated in a manner to warrant significant action by impacted sectors and stakeholders.

For example, the lack of public engagement in the ocean acidification issue is evidenced by the recent polling of the EU funded Climate Change and European Marine Ecosystem Research (CLAMER) project that is being managed by Centre for Environment, Fisheries and Aquaculture Science (Cefas) based in the United Kingdom. The CLAMER project undertook the first European poll ever about public perception of climate change in the marine environment. The purpose of the polling was to identify what the European public knows about, and how they perceive, climate change impacts in their seas in order to detect the main gaps in public awareness, and to highlight the issues that are considered important and/or urgent at a regional and Europe-wide level. The CLAMER poll surveyed a representative sample of European citizens (10,000 participants from 10 European countries[4]) taking in account differences between coastal and inland areas. The full results can be found online[5] but those relevant to ocean acidification are noted here (CLAMER, 2011):

a) Whilst understanding of some key topics is good (e.g. sea level rise), there is limited public awareness of some scientific issues (e.g. acidification), possibly reflecting a failure of communication in some instances (by scientists, project leaders, governments and policy makers). More emphasis is required on techniques to engage the public and on wider dissemination where awareness is lacking.

b) Ocean acidification was seen as a more immediate threat in Germany, Italy, France and the Czech Republic. In the UK and Norway, almost 30% of respondents said they did not know when impacts from acidification would become apparent (compared to the average of 18% for all countries combined). For acidification, those people visiting the Baltic, or the Black Sea thought this was already happening.

[4] Spain, Estonia, Germany, Italy, Norway, Ireland, Netherlands, UK, France and Czech Republic
[5] www.clamer.eu

c) Looking at the ranking of how informed and concerned the public are about marine environmental matters, it was interesting to note that it is pollution, a non-climate change issue that people were most concerned about. However a number of climate change issues featured relatively highly on the list of issues respondents were most concerned about, notably melting sea-ice, coastal flooding, sea level rise and changes in extreme weather events. There was relatively low awareness about oceans becoming more acidic, despite ocean acidification being a major EU research theme. This limited knowledge may be due to the fact that this particular issue seems less 'visible' than some of the other climate related impacts listed, and it remains unclear how and whether this long-term change will impact people's daily lives.

d) Public understanding of likely impacts (sea temperature change and sea level rise) tallied remarkably well with current scientific understanding, suggesting that the public has a fair degree of understanding or intuition about the likely magnitude of changes involved for these issues. With regards to when impacts might become apparent, it is arguably the most visible of those impacts, i.e. changes in extreme events, which the public perceived as the most immediate threats. The least 'visible' and most poorly understood impact, ocean acidification, was regarded as being the least immediate threat.

Considerable effort is made by the scientific community to establish a scientifically sound evidence for ocean acidification to inform decision-making processes, and raise public awareness. For example, the Ocean in a High-CO_2 World international science symposium series convenes the worlds leading scientists (2004, 2008) to discuss the impacts of ocean acidification on marine organisms, ecosystems and biogeochemical cycles, and in 2008 led to the Monaco Declaration; a call by over 150 leading scientists from 26 countries for immediate action by policy makers to reduce CO_2 emissions sharply so as to avoid widespread and severe damage to marine ecosystems from ocean acidification[6]. The Third Symposium on The Ocean in a High-CO_2 World, co-sponsored by Scientific Committee on Oceanic Research (SCOR), International Geosphere-Biosphere Programme (IGBP) and Intergovernmental Oceanographic Commission (IOC)/UNESCO, will be held in September 2012 in Monterey California and expects to attract over 300 of the world's leading scientists to discuss the impacts of ocean acidification on marine organisms, ecosystems, and biogeochemical cycles. It will also cover socio-economic consequences of ocean acidification, including policy and management implications[7].

To better understand what is relevant to policy makers, industry, media, etc., scientists must engage in further dialogue with these sectors to capitalize on their efforts while helping these sectors to better understand the strength of the evidence and what uncertainties exist in the scientific process (Turley and Boot, 2011). The combination of mutual understanding and effective communication (especially as a two way process) will ensure that science does not languish in the realms of academia but is put into practice to the betterment of the environment and society.

To achieve the traction and attention that the scientific community feels this issue deserves will require a better understanding of available communication mechanisms, target audiences (e.g. policymakers, fishermen, the media, school children, etc.) and

[6] http://ioc3.unesco.org/oanet/Symposium2008/MonacoDeclaration.pdf. Accessed 30.07.11
[7] www.highco2-iii.org

what resonates with them, as this may vary, and what lessons have been learned to date from previous ocean acidification communication efforts.

Communication of the complex issue of ocean acidification has not been straightforward, and the science may be lost if the communicator is not effective and clear in the delivery of their message. Mechanisms that are currently being employed to facilitate communication strategies have tried to build upon a general awareness of climate change and carbon emissions by linking ocean acidification and climate change together. At the same time the majority of the published scientific literature makes the distinction between climate change and acidification by referring to the changing ocean chemistry as a carbon issue rather than a climate change issue (Orr et al., 2009; Orr et al., 2005; Sabine, 2004; Royal Society, 2005; IPCC, 2007). Ocean acidification is also more often then not depicted as an issue that is a 'serious threat' to our oceans (Harrould-Kolieb et al., 2010), and only eluding to climate change in the context of existing threats in the marine environment that acidification could aggravate and exaggerate (Plymouth Marine Laboratory, 2007).

Statements about the issue, conveying a sense of doom and gloom through bleak predictions for the future of our oceans are not uncommon (One World; NRDC; InterAcademy Panel, 2009; Plymouth Marine Lab, 2007; Feely et al., 2004). Frequently used terms include "extinction," "threat," "change," and "alarming," applying a 'Pandora's Box' frame denoting the potentially catastrophic, dangerous ramifications leading to such statements as "the prospect of ocean acidification is potentially the most serious of all predicted outcomes of anthropogenic CO_2 increase" (Veron, 2008). Trying to elicit action and concern by portraying a less than optimistic outcome is another popular mechanism commonly used to communicate about acidification. However, this may not be the most helpful approach given the panoply of other concerns and worries that society has to consider today with respect to the ocean and who are inundated regularly through the mainstream media of the doom and gloom associated with the ocean.

More recently, articles have begun to address the risk to coral reefs, an enigmatic, highly visual ecosystem with recognizable biological and economic importance (National Academies, 2010; Reynaud et al., 2003; Anthony et al., 2008). Articles frame the ocean acidification issue within the context of threats to coral reefs, building upon the public's understanding of, and connection to, these ecosystems to generate concern, interest and political buy in (Miles and Bradbury, 2009).

In addition to the numerous easy to read and jargon free reports, leaflets and briefing documents, videos have become an increasingly popular format used to convey information about ocean acidification to the public and policy makers, with over 600 video presentations concerned directly or indirectly with ocean acidification and available online via YouTube. These include such titles as *Acid Ocean* (Stanford University), *Acid Test* (NRDC), *Ocean Acidification in a Nutshell* (Greenpeace), *Ocean acidification: Connecting science, industry, policy and public* (EPOCA), *The Other CO_2 problem* (Ridgeway School, UK) and others which are generally being circulated through environmental list serves and shown at policy briefing events. Two feature length films have also been produced *A Sea Change* and *Tipping Point* that explore the confluence of the ocean acidification science and relevance to society.

Several sites aggregate information, including the Ocean Acidification Network[8], European Project on Ocean Acidification (EPOCA)[9] and the Ocean Acidification blog[10], in

[8] www.ocean-acidification.net
[9] *www.epoca-project.eu*

addition to a handful of website pages dedicated to acidification housed by NGOs and government organisations (e.g. Oceana, NOAA, NRDC, Center for Biological Diversity, etc). There is no popular or advertised platform that actively communicates the latest science, policy and thinking around acidification to a broad audience with any regularity. Most of the articles are communicated through niche list serves (fishing or scientific community), as static webpages, or as singular articles on a blog or newspaper.

Since the release of the Royal Society's ocean acidification report (2005) there has been increasing political uptake but this has primarily been limited to Europe, North America, Australia and New Zealand. This has led to considerable funding being directed towards ocean acidification research in these locales. These resources have largely been leveraged on the back of the recent outputs from symposiums and the publication of reports, which provide a clear overview of the issue and the potential impacts on marine ecosystems, and thus raised the profile of the topic with politicians and the conservation community. It is clear that open, well-informed responses, couched in terms that the various stakeholder groups can understand, based on knowledge rather than supposition, is paramount.

Dialogue through initiatives such as the International Ocean Acidification Reference Users Group (RUG) concept has proven to be effective in ensuring the relevance, usefulness, and dissemination of results from ocean acidification research. The RUG was established in 2008 to support the work of the European Project on OA (EPOCA), and has evolved to provide support to complementary studies in Germany (BIOACID) and the UK (UK OA Research Programme), with strong links in similar processes in the USA. The RUG draws together a wide range of end users (representing the policy, environmental, industry, and conservation sectors) to support the work of leading scientists (OA RUG, 2010). Two-way exchange of knowledge between scientists and end users from the outset of the research projects has ensured that the science is policy relevant. RUG members gain knowledge useful to their respective organisations, and this approach has often stimulated organisational activities in knowledge exchange or in some instances collaboration among members, while scientists get direct feedback from stakeholders on what the key policy questions and issues are for a wide range of stakeholders and how they can make their science more accessible and credible to users. Such feedback has already ensured that scientists are looking at policy relevant CO_2 concentrations, and this direct interaction with stakeholders will help 'ground truth' knowledge exchange activities and products for the research programs.

Communication and market research around perceptions and understanding of ocean acidification amongst the public was conducted in late 2010 in the UK and the United States (Dropkin, 2011)[11]. Results from the focus groups, and surveys undertaken, indicated that for there to be any successful effort in addressing ocean acidification that it should be left out of the climate debate and established as a problem in its own right. The criterion for success was noted as avoiding the framing of ocean acidification as "yet another environmental problem." Instead any communications effort, founded in robust and good science, should firmly establish that:

- Ocean acidification is real and happening (not an agenda or scare tactic) with science to support it;

[10] www.oceanacidification.wordpress.com

[11] The survey was conducted in the United States and the United Kingdom in January 2011. The US survey sample size was 1898 adults aged 18 and was controlled for demographic and geographic representation of the population. The margin of error for the US sample is +/- 2.3 percentage points at the 95% confidence level. The UK survey sample size was 1211 adults aged 18 and over and was controlled for demographic and geographic representation of the population. The margin of error for the UK sample is +/- 2.8 percentage points at the 95% confidence level.

- Ocean acidification is relevant to life and society (there are visible consequences that affect the public); and that
- Future impacts are serious enough that it is worth acting now to avoid the consequences (urgency).

Status of Policy Integration

Policymakers require an objective source of information about the causes of climate change, its potential environmental and socio-economic consequences, and the adaptation and mitigation options to respond to it (Turley and Boot, 2011). The changes in ocean carbonate chemistry generated by ocean acidification are occurring at such a rapid rate that there is little time to produce the level and amount of knowledge necessary to produce an unambiguous input to policy makers. Policy action is therefore required before a comprehensive understanding is available (Gattuso and Hansson, 2011), and accordingly the nature of ocean acidification and its potential consequences has not achieved the 'pull through' to policy makers that its nature might warrant (Turley and Boot, 2011).

The following section outlines the principle policy mechanisms available for the consideration of ocean acidification, and the current status of integration given the nascent nature of this issue.

UN Convention on Biological Diversity (CBD)

Ocean acidification has gained increasing attention at the CBD's biennial meetings of the Conference of the Parties (COP) due to concern regarding the risks posed by ocean acidification to marine and coastal biodiversity, and the implications for achievement of the CBD mandate. The urgency and specificity reflected in the decisions adopted within the CBD is unprecedented for an international treaty body addressing ocean acidification.

At the ninth meeting of the Conference of Parties to the Convention, the Executive Secretary was requested to compile and synthesize available scientific information on ocean acidification and its impacts on marine biodiversity and habitats (Decision IX/20 – marine and coastal biodiversity). The synthesis was made available for consideration by the Subsidiary Body on Scientific and Technical and Technological Advice (SBSTTA), at its fourteenth meeting, and used to inform discussions on the treatment of ocean acidification within the context of the marine and coastal Programme of Work at the 10th meeting of the Conference of Parties (COP) in 2010. The Secretariat of the CBD also jointly convened a side event on ocean acidification during CBD COP10 to raise awareness of the issue among country Parties, and disseminate contemporary scientific knowledge.

The Conference of Parties to the CBD in decision X/29, '*Expresses its serious concern that increasing ocean acidification, as a direct consequence of increased carbon dioxide concentration in the atmosphere, reduces the availability of carbonate minerals in seawater, important building blocks for marine plants and animals*' and '*Takes note that many concerns exist regarding the biological and biogeochemical consequences of ocean acidification for marine and coastal biodiversity and ecosystems, and the impacts of these changes on oceanic ecosystems and the services they provide, for example, in fisheries, coastal protection, tourism, carbon sequestration and climate regulation, and that the ecological effects of ocean acidification must be considered in conjunction with the impacts of global climate change*'.

At its 10th meeting, the Conference of Parties to the CBD requested the Executive Secretary to develop a series of joint expert review processes to monitor and assess the impacts of ocean acidification on marine and coastal biodiversity and to widely disseminate the results of this assessment (Decision X/29 – marine and coastal biodiversity). Parties were also encouraged to take account of emerging knowledge on ocean acidification and to incorporate it into NBSAPs and national and local marine and coastal management plans (CBD, 2010).

The expert review process is intended to identify an appropriate mechanism to enable continued integration of the evolving scientific knowledge on ocean acidification into the CBD process, and to successfully disseminate this information to the 193 Parties to the Convention. An expert meeting will be convened to further discussions on an appropriate expert review process, and to provide a perspective on the status of science and policy integration. Suggested approaches will be submitted to the 16th meeting of the SBSTTA in 2012.

Given the relationship between atmospheric carbon dioxide concentration and ocean acidification, the Executive Secretary was requested to transmit the results of these assessments to the Secretariat of the United Nations Framework Convention on Climate Change (UNFCCC). While the CBD is not a focal point for discussions on climate change or GHG emissions reductions, its decisions are often influential in the development of international norms relating to the ocean, including those within the climate change nexus. Current linkages between CBD and UNFCCC are limited, however the responsibility and opportunity to enhance cooperation for the achievement of the two inter-related yet distinct mandates is recognised (SCBD, 2010), and should be further developed.

In decision X/2, the 10th meeting of the Conference of the Parties adopted a revised *Strategic Plan for Biodiversity*, including 20 specific targets for the period 2011-2020 (Aichi Biodiversity Targets). Target 10 includes further reference to ocean acidification: '*By 2015, the multiple anthropogenic pressures on coral reefs, and other vulnerable ecosystems impacted by climate change or ocean acidification are minimized'.* In 2014 Parties will be required to report national progress towards the Aichi Biodiversity Targets and capacity building workshops are currently underway to assist countries in establishing relevant national targets to respond to this framework[12].

UN Framework Convention on Climate Change (UNFCCC)

The UNFCCC is the principle international forum for addressing the causes and effects of climate change and is considered an appropriate policy regime to respond to mitigation of ocean acidification, through CO_2 emission reductions. Furthermore, it is a suitable forum for devising and providing funding for responses to ocean acidification that can be incorporated into national adaptation plans (Harrould-Kolieb and Herr, 2010).

The ocean is one of the largest natural reservoirs of carbon, absorbing ~26–29% of anthropogenic carbon emissions each year. However, the oceans' capacity to absorb atmospheric CO_2 is being degraded by ocean acidification, which will make it more difficult to stabilize atmospheric CO_2 concentrations (Hood et al., 2009). In the absence of anthropogenic CO_2 uptake by the oceans, atmospheric CO_2 levels would be ~55 ppm higher than present, and the effects of global climate change more marked (Solomon et al., 2007). In view of the vital role of the oceans in the carbon cycle, and the predicted implications for the continued provision of this important service, ocean acidification is of specific relevance within the context of the Convention.

[12] www.cbd.int/nbsap. Accessed 11.07.11

In 2009, the Inter-Academy Panel on International Issues (IAP) released a statement on ocean acidification, endorsed by 70 of the world's leading scientific academies, calling for ocean acidification to be considered in the international climate change debate, and recommending the urgent reduction of global emissions of CO_2 by at least 50% by 2050 to stabilise temperature increases and acidification at sub-critical levels (IAP, 2009).

The risk to marine ecosystems from ocean acidification received little attention in the UNFCCC COP15 negotiations at Copenhagen in 2009 (Turley and Boot, 2011) and to date, no concrete recommendations have been made on how ocean acidification could be integrated within the Convention (Harrould-Kolieb and Herr, 2010). In order to ensure that ocean acidification is effectively considered, the Convention will need to institute changes to bring the evolving scientific knowledge of ocean acidification into its already existing framework and mechanisms (Harrould-Kolieb and Herr, 2010).

Other International Processes

The Intergovernmental Panel on Climate Change (IPCC)

The Intergovernmental Panel on Climate Change (IPCC) was established by the World Meteorological Organization (WMO) and the United Nations Environment Programme (UNEP), as a scientific body to provide collective evidence, scientific consensus and assessment of the risks of climate change for policy makers (Turley and Boot, 2011). The IPCC process represents a critical mechanism not only for building global scientific consensus on ocean acidification, but also for integrating ocean acidification concerns into negotiations aimed at reducing CO_2 emissions (Orr et al., 2009). Ocean Acidification was recognized by the IPCC in the 4th Assessment Report as a risk caused by increasing CO_2 emissions (IPCC, 2007), and in view of the growing body of research evidence, increased recognition of ocean acidification is anticipated in the 5th Assessment Report due in 2012 (Turley and Boot, 2011).

United Nations General Assembly (UNGA)

The United Nations General Assembly plays an essential role in ocean policy development and is charged with undertaking an annual review and evaluation of the United Nations Convention on the Law of the Sea and other developments relating to ocean affairs and the law of the sea, including in relation to oceans and climate change.

At its 65th Session, the General Assembly adopted a resolution on coral reefs which '*Urges States, within their national jurisdictions and the competent international organisations, within their mandates, given the imperative for action, to take all practical steps at all levels to protect coral reefs and related ecosystems for sustainable livelihoods and development, including immediate and concerted global, regional and local action to respond to the challenges and address the adverse impacts of climate change, including through mitigation and adaptation, as well as of* ***ocean acidification*** *on coral reefs and related ecosystems*' (UNGA, 2010).

The Assembly also adopted a resolution on "**oceans and the law of the sea**" (A/RES/65/37) which '*notes the work of the Intergovernmental Panel on Climate Change, including its findings on the acidification of oceans, and in this regard encourages States and competent international organisations and other relevant institutions, individually and in cooperation, to urgently pursue further research on ocean acidification, especially programmes of observation and measurement*' (ICRI, 2010)**.**

The Intergovernmental Oceanographic Commission (IOC) of UNESCO

In May 2004, the SCOR and UNESCO-IOC co-hosted an international symposium "The Ocean in a High-CO_2 World", to evaluate the status of knowledge on ocean acidification.

The symposium convened the world's leading scientists with expertise in different branches of marine biology, chemistry and physics to piece together known impacts of ocean acidification on marine ecosystems, and to identify urgent research priorities to understand the mechanisms, magnitude and time scale of these impacts. SCOR, the IOC in collaboration with the International Geosphere-Biosphere Programme (IGBP) and other agencies continue to review the issue of ocean acidification, providing a critical forum to scientists every four years.

The Research Priorities Report produced as a result of the Symposium represents an authoritative assessment of what is known about ocean acidification impacts. In 2009 this report informed the Monaco Declaration, supported by more than 150 leading marine scientists from 26 countries, which called for immediate action by policy makers and the climate change research community to take ocean acidification into account.

United Nations Commission on Sustainable Development
The Commission on Sustainable Development will consider the issues of oceans and seas and small islands developing states in 2014 and 2015 and will provide an opportunity to highlight ocean acidification and take policy decisions aimed at combating it (UN-DESA, 2009).

Regional Processes

Convention for the Protection of the Marine Environment of the North-East Atlantic (OSPAR Convention): The OSPAR Convention provides a framework for the coordinated management and regulation of increasing demands for the uses of the North East Atlantic and for ensuring that these activities do not adversely impact the marine environment. The OSPAR Commission is an active member of the global group of Regional Management Organisations and cooperates closely with its partner organisations (e.g. UNEP Regional Seas Programme).

Ocean acidification is recognised within the context of the Convention. OSPAR will have a key role in monitoring and assessing regional ocean acidification impacts on the marine environment, and is working to integrate climate change issues into all its work areas (e.g. fisheries management) through active cooperation with partner organisations. Methods and indicators for monitoring the progression of ocean acidification impacts at regional scales are noted as a priority (OSPAR, 2009).

National and Local Processes

The United States Federal Ocean Acidification Research and Monitoring (FORAM) Act: Several environmental groups (e.g. Natural Resources Defense Council (NRDC), COMPASS, Environmental Defense Fund, etc.) have held policy briefings for congressional staff, convening policy makers and scientists to facilitate policy solutions. This has led to the development of the US Federal Ocean Acidification Research and Monitoring (FOARAM) Act passed in the House of Representatives and Senate respectively in March 2009. In response to the FOARAM Act, the U.S. government convened an Interagency Working Group (IWG) on Ocean Acidification, which began coordinating ocean acidification research activities across the federal government in 2009. The IWG includes representative from NOAA (chair), National Science Foundation (NSF), U.S Environmental Protection Agency (EPA), U.S. Department of State, U.S. Geological Survey, Fish and Wildlife Service, and Navy, and is developing an Ocean Acidification Strategic Research Plan for the US, which should be released in the next year.

The Act also mandates that NOAA has an active monitoring and research program to determine potential impacts of decreased ocean pH and carbonate saturation states. As a result, NOAA has also recently established an Ocean Acidification Program that serves as an important organizing entity for NOAA ocean acidification research, and for interagency and international activities. The NOAA OA Program is co-sponsoring the International Ocean Acidification Observing Workshop to happen in spring 2012. Other mandates such as the National Marine Sanctuaries Act, Endangered Species Act, Coral Reef Conservation Act, and Clean Water Act also require that NOAA work to fully understand the consequences of a changing environment to marine resources (NOAA, 2010). To provide strategic science based guidance to the NOAA research community, a consensus research strategy has been prepared, designed to advance understanding on the variable impacts of ocean acidification and to provide information that can be used by research managers to address acidification issues.

Status of Other Stakeholder Integration

The primary stakeholders involved in the ocean acidification are scientists, governments, members of the fishing and seafood industry, donors, media and the environmental advocacy groups. Each has engaged with the ocean acidification issue(s) to varying degrees and communication efforts remain very much targeted to specific audiences with an education or policy agenda, but excluding the general public so far.

Where other sectors are further advanced in their engagement the seafood industry, broadly speaking, has been slow to engage with the issues and potential impacts of ocean acidification on their industry and livelihoods. This is rapidly changing as they learn more about the issue and try to ascertain how to position it within their industry.

Over the last two years there have been a number of initiatives and concerted effort to bring members of coastal communities and industry with a strong dependence on the shellfish industry into the debate, cut through the complexity and make them part of the solution(s). Especially relevant as about 50% of U.S. primary fishery revenue is from shell- forming mollusks and crustaceans (Cooley and Doney, 2009).

Given the potential impact that ocean acidification may have on the seafood industry it is looking for ways to educate themselves, engage with the most up to date science, share knowledge and gain traction on this issue. Many of the world's largest companies are actively seeking to better understand and confront these large environmental problems in hopes that they can mitigate any negative effects on business. Through a series of recent workshops (2009 to present) and international meetings (Seafood Summit 2010 and 2011), targeted at the fishing industry and being undertaken by several organisations (e.g. SeaWeb and the Sustainable Fisheries Partnership), the current science on ocean acidification has been highlighted, the projected effects on the global seafood industry discussed, and how stakeholders can use their collective influence and support to encourage positive change explored.

The workshops also considered several different vantage points – including:

- Latest research from the science community, resonance of the issue and messaging from communications experts (i.e. Dropkin 2011); and
- Lessons learned from those areas and sectors already experiencing the impact of ocean acidification and adaptive practices that are being adopted by the seafood industry (e.g. from more sensitive monitoring of ocean chemistry to considering breeding seafood to survive ocean acidification) See Box 1.

In September 2009 more than 100 fishing boats, sail boats, skiffs and kayaks took to the waters of Homer Alaska as commercial fishermen, mariners and others from coastal communities spelled out an urgent message to protect jobs and fisheries from the threat of ocean acidification. The boats arranged themselves in the ocean to spell out "Ocean Acid SOS" as part of a 'Voices for the Ocean' event hosted by the Alaska Marine Conservation Council (AMCC) and the Sustainable Fisheries Partnership (SFP).

While there is a general consensus among scientists that ocean acidification will negatively impact the marine environment, and that insufficient field study data fosters a degree of scientific uncertainty this allows industry and some other stakeholders to be at arm's length until it affects them directly (note Dropkin, 2011). Industry is not interested in seeing the words 'ocean acidification' and 'seafood' appear together at all for fear of starting food safety issue and public concern, but would rather the emphasis of their engagement be that of food security.

BOX 1

Crisis for United States West Coast Oyster Growers

For Taylor Shellfish, the largest farmed shellfish producer in the United States, acidification is not a future threat estimated by modelling or projections. During 2007-2009, Taylor Shellfish's hatchery production fell 70-80 percent. Other West Coast operations were also devastated. At the Whiskey Creek Hatchery in Netarts Bay, Oregon, oyster larvae dissolved in their tanks with even hard-fouling of the intake pipes having ceased. The staff at Taylor Shellfish believed corrosive water was a major factor and may well be part of why there had not been a wild set of Pacific oysters on the Washington coast for six successive years. Water with a pH as low as 7.4 had been drawn from Dabob Bay, where Taylor's main hatchery is located. Hatchery operators at Taylor and Whiskey Creek started monitoring CO_2 levels and adjusting the depth and time of day when they drew seawater in order to avoid CO_2-rich water that killing larvae. The two firms have been able to restore about 75 per cent of the larvae production that they lost in earlier years, showing that "bad water" can be dodged, at least for now. But immediate adaptation is only part of the solution for Taylor and other shellfish producers. Longer range, oyster growers are trying to cultivate more resilient broodstock, with scientists at Oregon State University and the U.S. Department of Agriculture's (USDA) Agricultural Research Service leading the research. Taylor Shellfish has become an active participant and advocate in promoting continued research, increased monitoring, and reduced carbon emissions. The science indicates that current corrosive water upwelling that is regularly shoaling on the US west coast is fifty years old, which strongly suggests that this problem isn't going away anytime soon. As such Taylor Shellfish feels obligated to speak out and make others aware of the serious consequences of carbon emissions from the first hand experiences. Their story is an important one to help influence their peers in the seafood industry to take a more proactive approach to address ocean acidification. (From: Eric Swenson, Fish Information Service (*FiS)*, 21 February 2011)

Limitations for communications/barriers to uptake of messages

Despite the dominance of the ocean ecosystem only a small percentage of humanity has actually 'seen' the underwater environment. This is hardly surprising given that from an early age children are taught (via maps and geography classes) that land has definition, boundaries, populations, countries/cities, etc. but the ocean is a big, blank blue space, and the threats to it are thus difficult to convey in a way that resonates with the public, industry and policymakers alike. Though this is changing in policy circles (e.g. Millennium Ecosystem Assessment and the Biodiversity Indicators Partnership[13]) this has lead to a predominance of out-dated and misinformed perceptions of the ocean, with society under valuing the ecosystem goods and services, which the ocean provides. This holds true despite the fact that natural scientists have been collecting ocean related data and producing detailed analyses for centuries.

Given the level of ocean knowledge that scientists have to operate from with respect to raising the awareness of new and emerging ocean issues with society it is understandable that a complex issue, such as ocean acidification, does not have greater uptake and resonance with the public at large.

Declarations of concern about the condition of the marine environment are prevalent, but there is a general lack of concerted action. Barriers and limitations to the uptake of ocean acidification messages and science is being driven by a range of factors, including such things as (amongst others):

- Ocean acidification (and climate change) is low on the list of public perceptions of threats to the ocean (Dropkin, 2011).
- The scientific evidence of ocean acidification, filtered by the media and some in the conservation community, increasingly presents 'doom and gloom' scenarios laden with jargon that the general public does not understand. As a result, the information and messages either do not resonate or it scares them into inaction. Evidence suggests that this 'fear framing' may be more counterproductive by encouraging audiences to switch off, when they really need to be switching on (Ereaut and Segnit, 2004). That being said and despite recent 'climate gate' issues scientists are still the most trusted by the public to give truthful information about ocean acidification (Dropkin, 2011).
- Most of the general public perceive marine conservation issues from a distance (i.e. it is someone else's problem or it is a problem for the future), and have little personal experience from which to draw upon. Because of this distance, their approach to ocean conservation is from an analytical mode that is influenced by pre-formed 'mental models' (often misinformed and as a result erroneous), rather than from an emotional angle that will more often lead people to make necessary behavioural changes. Hearing about ocean acidification has been found to generate wide, but not deep concern, as the consequences are believed to be in the future (Dropkin, 2011). However, when the impacts of ocean acidification were localised with the general public this created the greatest sense of real consequences that are happening today (Dropkin, 2011). A point of note when considering ocean acidification communication strategies.
- Even though people are generally concerned about the environment they do not place this on equal footing with issues related to the economy, health, welfare, war

[13] www.bipindicators.net

and peace. The intimate connection between these issues and the ocean has not been effectively communicated and by extension ocean acidification falls into the latter category.

- The majority of people have out-dated perceptions of the ocean and view it as immense, bountiful, inexhaustible, infinitely resilient and impervious to human influence. Thus the role of the living ocean is not firmly cemented in the public mind, and as such do not feel that ocean acidification is something to worry about despite the evidence and predictions (Dropkin, 2011).
- The perception that problems facing the ocean are huge and vast is so pervasive that people do not see how their individual actions can make any difference. This is the same situation with ocean acidification, which has become intertwined with climate change (Maiback, 2008), and as a result the majority of the public feel polarized with a feeling of inability to have an impact on CO_2 emissions.
- The bulk of ocean acidification research to date has primarily taken place in developed countries. Vast gaps of understanding and awareness of ocean acidification exist in the developing world yet the potential impacts and consequences in these parts of the ocean are large. Little effort to date has been made to reach this geography of the scientific community and public with only EPOCA having made some inroads by making their ocean acidification policy briefs available in other languages.[14]

The challenge remains to ensure that ground-breaking science on ocean acidification addresses the questions that need to be answered, and that these answers get quickly and effectively into the hands of policy makers and decision makers so that action can be taken while at the same time relaying the appropriate level of detail to society at large. Upon examination of the potential benefits and consequences of framing ocean acidification within the broader climate change debate, the risk of transferring the negative imagery and emotions linked to climate change outweigh the potential benefits of association. Moreover, advocates for action on ocean acidification could unintentionally be amplifying the inherent uncertainty associated with the issue by linking it to the uncertainties surrounding ocean-related climate impacts. Therefore, a separate frame would best serve all future ocean acidification communication strategies (Lewis-Koskinen, 2011).

Conclusions from the recent market and communication research (Dropkin, 2011) are instructive in order to consider how best to frame the communication of ocean acidification and avoid building further barriers.

- Ocean acidification is another problem to be concerned about but not sense of immediacy.
- The terminology sets the frame and “ocean acidification” while descriptive, is passive.
- There is no clear guidance on the practical solutions or mitigation measures of ocean acidification other than CO_2 emission reduction.
- Ocean acidification has much lower concern and awareness than other ocean problems.
- The “ocean” is a big place, vague and individuals inclined to think it is beyond their control.
- People respond to what they see and ocean acidification is invisible problem.

Only about two percent of all research dollars for climate change is spent on the human dimension even though it is widely recognized that the biggest hurdle to addressing

[14] http://www.epoca-project.eu/index.php/what-do-we-do/outreach/rug/oa-questions-answered.html

climate change is not technology but changing human behaviour (CRED, 2009). An important lesson from the climate change domain suggests that the ocean acidification community at large (including science, donors, conservation, industry and policy sectors) should consider adequately resourcing the removal of barriers to the communication and message uptake of ocean acidification. By removing these barriers there is a belief that there will be an enhanced uptake and resonance with all aspects of society.

Overall ocean acidification is an issue "waiting to be made" but will require a strategy of clear and coordination science and communications that makes the problem's consequences relevant today at a personal level (Dropkin, 2011).

Consideration for Developing a Joint Expert Review Process

In view of existing knowledge and experience, the following issues are proposed as important elements in guiding the consideration of ocean acidification within the context of the CBD and its implementation at the national, regional and global levels. These elements, and the suggested approaches, are intended to assist deliberation of the upcoming CBD Expert Meeting on Ocean Acidification (Montreal, 19-20 October 2011), as to the optimal engagement of the CBD and relevant partners on this issue.

Consider emerging science on ocean acidification
Research effort is underway to improve understanding of the likely implications of ocean acidification for marine and coastal biodiversity, ecosystems and human societies. To enable the consideration of new knowledge, and the effective transmission of this information to Parties for improvements in mutual understanding of the issues and the development of responsive guidance, further work will be needed to:

- Undertake a regular assessment of ocean acidification science and provide inputs of known and predicted impacts of ocean acidification on marine and coastal biodiversity to the Conference of the Parties;
- Facilitate integration of ocean acidification assessment outcomes across all relevant Programmes of Work within the Convention, such as Island Biodiversity, Protected Areas, and Biodiversity for Development;
- Establish effective linkages with international ocean acidification research coordination efforts (e.g. IOARUG) for the effective transfer of contemporary research; and
- Encourage dialogue, as appropriate, regarding the development of an indicator by which to measure the impact or successful mitigation of ocean acidification, in order to inform effective ocean acidification policy.

Support coordinated improvement of global understanding and knowledge sharing on ocean acidification
As national research activities on ocean acidification emerge worldwide it will become increasingly important to facilitate coordination and exchange among the key overarching activities, at an international level, to generate a comprehensive understanding of the global effects of ocean acidification and enable timely integration of scientific advice into policy frameworks. To support information exchange and decision making among Parties, further work will be needed to:

- Establish a platform or learning network to assist countries, in particular developing countries, including the least developed countries and small island developing states, to improve their understanding and assessment of the impacts, vulnerability and adaptation to ocean acidification and to make informed decisions on practical adaptation actions and measures based on sound science;
- Strengthen and support already on going national research efforts on ocean acidification, especially in priority research areas identified as critical to advancing collective global knowledge e.g. socio-economic impacts and vulnerable regions, through appropriate collaborations;
- Recognise and adopt international best practices in the observation of ocean acidification impacts in open-ocean and coastal environments, and the subsequent management of data resulting from national activities; and

- Compile and analyse case studies as well as any other relevant information relating to lessons learned across thematic programmes and cross cutting issues on aspects of ocean acidification monitoring, assessment, adaptation and research priorities.

Catalyse mainstreaming and integration of ocean acidification into national and regional biodiversity strategies and action plans

NBSAPs are the principle instruments for implementing the Convention at the national level. The Convention requires countries to prepare a NBSAP and to ensure that this strategy is mainstreamed into the planning and activities of all those sectors whose activities can have an impact (positive or negative) on biodiversity. To facilitate the effective incorporation of emerging scientific knowledge on ocean acidification into NBSAPs, national and local plans on integrated marine and coastal area management, and the design and management of plans for marine and coastal protected areas, further work will be needed to:

- Develop guidance and training modules to assist countries to incorporate ocean acidification knowledge into national planning processes, including NBSAPs, MPA planning, IMCAM, etc;
- Convene capacity building workshops at a range of scales (or integrate ocean acidification concerns into on going capacity building workshops) to assist countries in understanding the implications of ocean acidification for achieving the Aichi Biodiversity Targets, and to inform revision and updating of NBSAPs, ensuring that these are action-orientated and practical;
- Make available translations of existing educational, training and awareness raising materials prepared on ocean acidification for key audiences (and particularly for developing countries) to ensure consistent messaging and more effective use of resources;
- Establish a knowledge and information-sharing hub specific to ocean acidification with a view to enhancing the integration of efforts and interactions among countries, partners and other stakeholders; and
- Articulate country-specific goals, challenges and capacity building needs in monitoring and assessing the impacts of ocean acidification on marine and coastal biodiversity.

Create synergies among key international Conventions and processes;

There is a pressing need not only to ensure consistency, but also to minimize redundancy in the science effort used to inform the various international Conventions and processes - each of which is guided by its own scientific advisory group (e.g. The Subsidiary Body for Scientific, Technical and Technological Advice (SBSTTA) to the CBD; the Subsidiary Body for Scientific and Technological Advice (SBSTA) of UNFCCC; the Scientific and Technical Review Panel of RAMSAR). While the overall magnitude of the workforce is no longer a major impediment for ocean acidification research (Gattuso et al., 2011), the demands on researchers time remain high. In view of this, and the need for ocean acidification to be better recognised and integrated into the global CO_2 emission reduction debate, further work will be needed to:

- Work in collaboration with the Secretariat of the UNFCCC and other relevant Conventions and processes (e.g. IPCC) to further the integration of ocean acidification issues into the UNFCCC, and discussions on climate change and geo-engineering;
- Identify and advance opportunities for a thematic partnership or the establishment of a joint work programme on ocean acidification with the UNFCCC Secretariat to facilitate dialogue and exchange;

- Catalyse a strong and unequivocal statement of concern on ocean acidification impacts in the IPCC in its 5th Assessment Report, and request SBSTTA to take up the relevant recommendations of this group;
- Utilize the convening potential of international meetings and symposia to enhance periodic communication and cooperation on ocean acidification (e.g. 3rd Symposium on Oceans in a High CO_2 World (2012); Planet under Pressure meeting (2012); RIO +20);
- Ensure that there is common language and a set of harmonized principles to address ocean acidification and used by MEAs;
- Allocate resources to support policy integration; and
- Acknowledge the proposal for an Ocean Acidification International Coordination Office (OA-ICO) and the existing efforts for scientific collaboration at the international scale and identify how this will link into international fora and processes for timely integration of policy advice.

Conclusion

Ocean acidification is rapidly moving and expanding field with the level of interest, published literature and media coverage having increased exponentially over the last decade. There has been a commitment of considerable resources made available to support ocean acidification research, primarily in Europe and North America, and in some cases to undertake major, large scale, multi-year projects. This level of effort has led to significant advances in our understanding of this phenomenon, and while it has given rise to a fair number of 'certainties' it has also equally spawned numerous uncertainties to be addressed and questions still to be answered, as discussed throughout this document.

It is these unanswered elements which present a challenge in establishing ocean acidification as an issue that will touch all elements of society irrespective of geography, and which requires attention to seek solutions at the level of local community councils through to the offices of heads of state. Connecting with affected elements of society and policy makers is highly dependent on being able to effectively communicate the science and place it in the proper context that gives it resonance and relevance.

The International Ocean Acidification Reference Users Group (IOARUG) is a good example of connecting ocean acidification science with policy and society. IOARUG has achieved significant success in ensuring the production of sound science by maintaining a high degree coordination between ocean acidification research efforts in Europe, and increasingly in other areas worldwide. However, in order to maintain this momentum and to continue to attract the resources for ocean acidification research, which includes increased and sustained engagement with policy makers to solidify agreements towards solutions, there is still much to be done to convince the general populous that this is an issue very much in their interest to have their respective governments address.
This review noted strong evidence for the need to undertake a dedicated and targeted programme of action that connects scientists, business and industry, policymakers and journalists to build capacity for long-term solutions.

The risks posed by ocean acidification to environmental, financial, and social structures necessitate consideration of this issue in a variety of policy arenas. Policy makers, scientists and practitioners need to work together to ensure the most up-to-date information underpins developing policy to overcome the threats posed to human society. This collaboration must be arranged in such a way as to avoid unnecessary duplication, mindful of the limited pool of experts in this field and the already significant demands on their time.

The expert review process represents an opportunity to identify and establish appropriate mechanisms to better integrate ocean acidification concerns into the CBD and its implementation at the national, regional and global levels, and will enable exploration of relevant policy options. Mechanisms agreed should assist Parties, other governments and organisations to take into account the emerging knowledge on ocean acidification, and facilitating international cooperation to begin to develop solutions.

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