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Ocean Acidification
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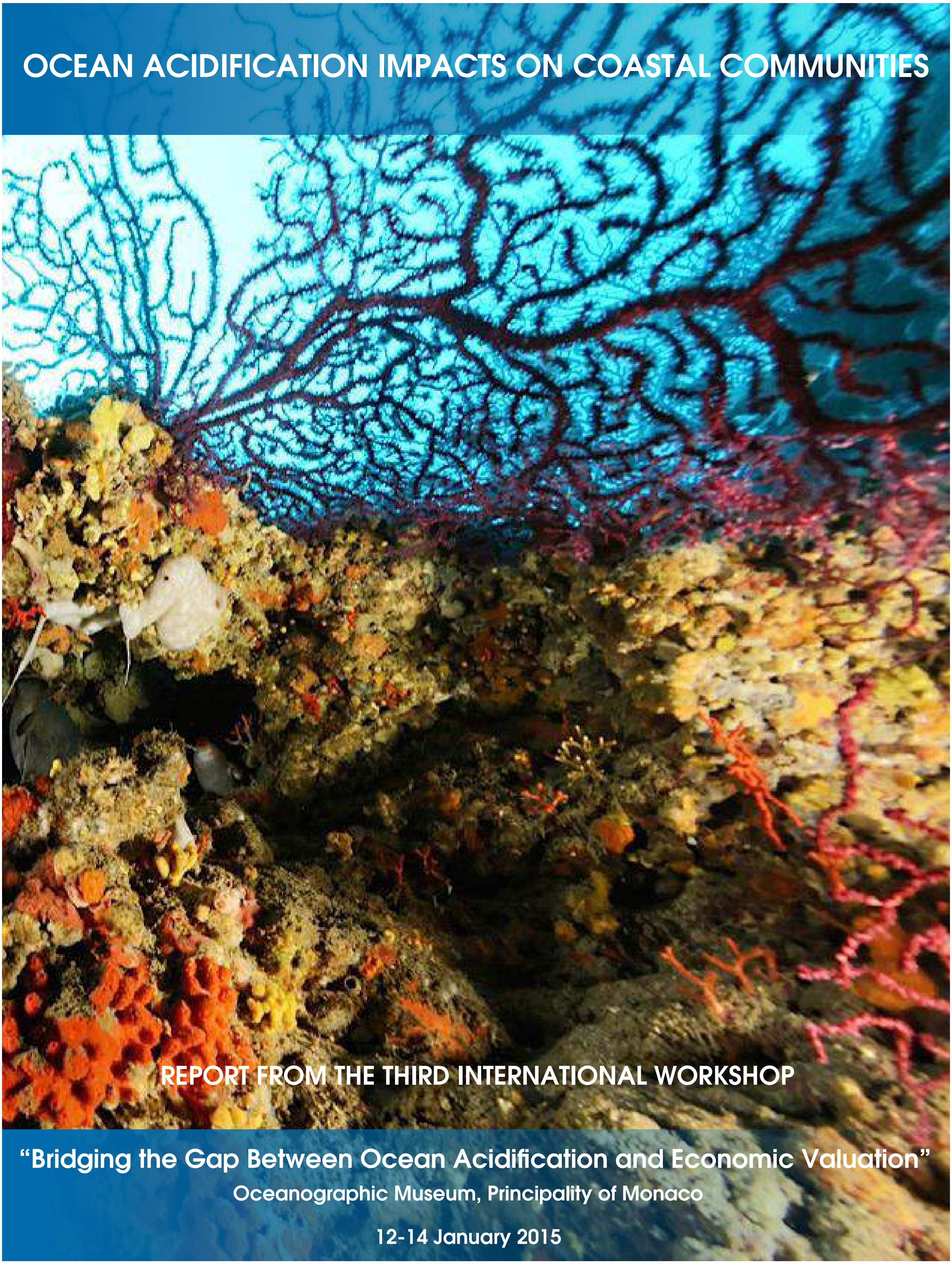
OCEAN ACIDIFICATION IMPACTS ON COASTAL COMMUNITIES



REPORT FROM THE THIRD INTERNATIONAL WORKSHOP

"Bridging the Gap Between Ocean Acidification and Economic Valuation"

Oceanographic Museum, Principality of Monaco

12-14 January 2015

INTRODUCTION

HSH Prince Albert II of Monaco - © Palais Princier

«Ocean acidification is, I believe, one of the greatest scourges resulting from the considerable development of anthropogenic greenhouse gas emissions, to have both concrete and global impact.»
H.S.H. Prince Albert II of Monaco

Ocean acidification is a growing environmental concern. The chemistry and, therefore, biology of world oceans will be impacted to different degrees, depending on the region and the type of ecosystem. As a result of its impacts on marine organisms and ecosystems, ocean acidification has the potential to seriously affect the livelihood of coastal communities and their economies. From mega-cities to subsistence fishing villages coastal communities vary significantly in population, maritime activity, reliance on marine natural resources and therefore their respective degree of adaptability. Identifying the magnitude and types of consequences that ocean acidification could have on coastal communities will become a major concern for governments of coastal countries seeking to preserve current marine activities and benefits.

In 2008, the Monaco Declaration, drafted under the stewardship of HSH Prince Albert II of Monaco, advocated for a stronger collaboration between economists and natural scientists in order to better evaluate the socio-economic impacts of ocean acidification. In line with the Monaco Declaration and with the support of HSH Prince Albert II, an international workshop series - « Bridging the Gap Between Ocean Acidification Impacts and Economic Valuation » - was launched by the Centre Scientifique de Monaco (CSM) and the Environment Laboratories of the International Atomic Energy Agency (IAEA). Three workshops have been organized since 2010 all involving multidisciplinary international experts, to work on providing recommendations and an appropriate methodology for taking adapted policy measures or management options. These workshops resulted in a series of consistent, science-based conclusions and recommendations for policy makers.

The first workshop (2010) focused on the impacts of ocean acidification on the global economy. For the first time, economists and scientists came together to open the lines of communication and foster cooperation and coordination. The second workshop (2012) targeted the impacts of ocean acidification on fisheries and aquaculture in different regions of the world. Social and economic impacts of ocean acidification on livelihoods, commerce and food security were discussed.

The present document contains the core information issued from discussions during the third International Workshop. Fifty-three experts from natural and social sciences from 20 countries adressed the potential effects of ocean acidification on different coastal communities and what could be done about it.
Participants with backgrounds in various disciplines tried to evaluate possible impacts on major coastal fisheries and tourism activities, and considered ways to model the cascade of potential consequences of ocean acidification on human activities. They also examined potential adaptation and capacity-building options and policy responses available to these various sectors and governments. Each of the workshops provided a set of specific recommendations for policy makers on possible mitigation and adaptation measures, and research priorities.

OCEAN ACIDIFICATION AND COASTAL COMMUNITIES

Ocean acidification is a change in seawater chemistry caused by the absorption of excess atmospheric CO_2 by the ocean. A high-CO_2 ocean is predicted to have effects on marine organisms, including species upon which the economies of coastal communities depend. This could be through direct impacts on commercial species like shellfish, or indirectly *via* food web interactions and loss of marine habitats, such as coral reefs. These effects are inextricably linked to the impact of other stressors (e.g. warming, pollution, overfishing) on marine species and ecosystems.

This workshop focused on the socio-economic impacts of ocean acidification on coastal communities. Discussions centred around three main topics:

(1) coastal economic activities with a focus on fisheries, aquaculture and tourism; (chap.1 and 2)

(2) modelling as a tool to evaluate bio-socio-economic impacts of ocean acidification; (chap. 3)

(3) potential measures to tackle ocean acidification including societal action and adaptation, governance and legislation options. (chap. 4 and 5).

1. COASTAL COMMUNITIES DEPENDENT ON FISHERIES AND AQUACULTURE

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Context

Ocean acidification will affect dependent coastal communities in different ways. This summary examines:

1- the main impacts of ocean acidification on coastal communities dependent on fisheries and aquaculture;

2- the way in which these impacts affect different coastal communities;

3- the factors that determine community vulnerability;

4- a range of lessons learnt, policy options, strategies and actions. The summary concludes with several recommendations. Related issues on marine tourism, modelling of effects, governance and societal responses and knowledge management are addressed in the following chapters.

Ocean acidification is likely to have a proportionately greater negative impact on small scale producers, on subsistence fisheries, on poorer fishing communities and communities that are heavily dependent on fisheries and aquaculture. Many of these communities are also more vulnerable to a broad range of climate change impacts and have fewer possibilities for alternative livelihoods (Daw *et al.*, 2009).

About 38% of global marine capture fisheries production (80 million tonnes/year) is harvested by small-scale fishers, while they account for about 85% of the capture fisheries workforce (World Bank, 2012). Small scale producers constitute 88% of the aquaculture workforce (mariculture production is about 25 million tonnes/year, much of which is seaweed; FAO, 2014 a). Over 95% of small-scale marine fishers live in developing countries (World Bank 2012) with an estimated 6 million reef fishers in some 100 countries and territories worldwide (Teh *et al.*, 2013). Women represent almost half the small-scale fisheries workforce and approximately 25% of reef fisheries harvesters are gleaners (mostly women and children) collecting shellfish and other species in tidal areas (Kleiber *et al.*, 2014). These small-scale fishing communities are particularly vulnerable and a significant part of their production is used for direct local consumption. In recent decades, mariculture has accounted for an increasing proportion of marine food supplies (FAO, 2014 b) while recorded capture marine fisheries production has stagnated (FAO, 2014 b) with a declining proportion of assessed marine fish stocks (<10%) considered underexploited (FAO, 2014 b).

These trends are likely to continue as economies grow, as labour moves from fisheries into other sectors and as demand for fish increases with rising incomes.

Potential impacts of ocean acidification

The impacts of ocean acidification on coastal communities is inextricably linked to the impact of other stressors on species and ecosystems (Riebesell and Gattuso, 2015). Meta-analyses based on experimental data (Figure 1; Kroeker *et al.*, 2013) show that ocean acidification can have significant direct impacts on the productivity of many marine species, including species upon which the economies of coastal communities depend. In addition, the structure and integrity of ecosystems will be threatened through changes at different trophic levels. On a global scale, several trends can be identified. For example, calcifiers (species with shells or bones) are generally more sensitive to ocean acidification than the non-calcifiers, such as seagrasses and certain species of algae, (Figure 1; Kroeker *et al.*, 2013); (Figure 2; Wittmann and Pörtner, 2013). However, this impact is highly species-specific, making any extrapolation from one species, habitat or area to another difficult (Kroeker *et al.*, 2013).

Figure 1. Summary of effects of acidification among key taxonomic groups (from Kroeker *et al.*, 2013).

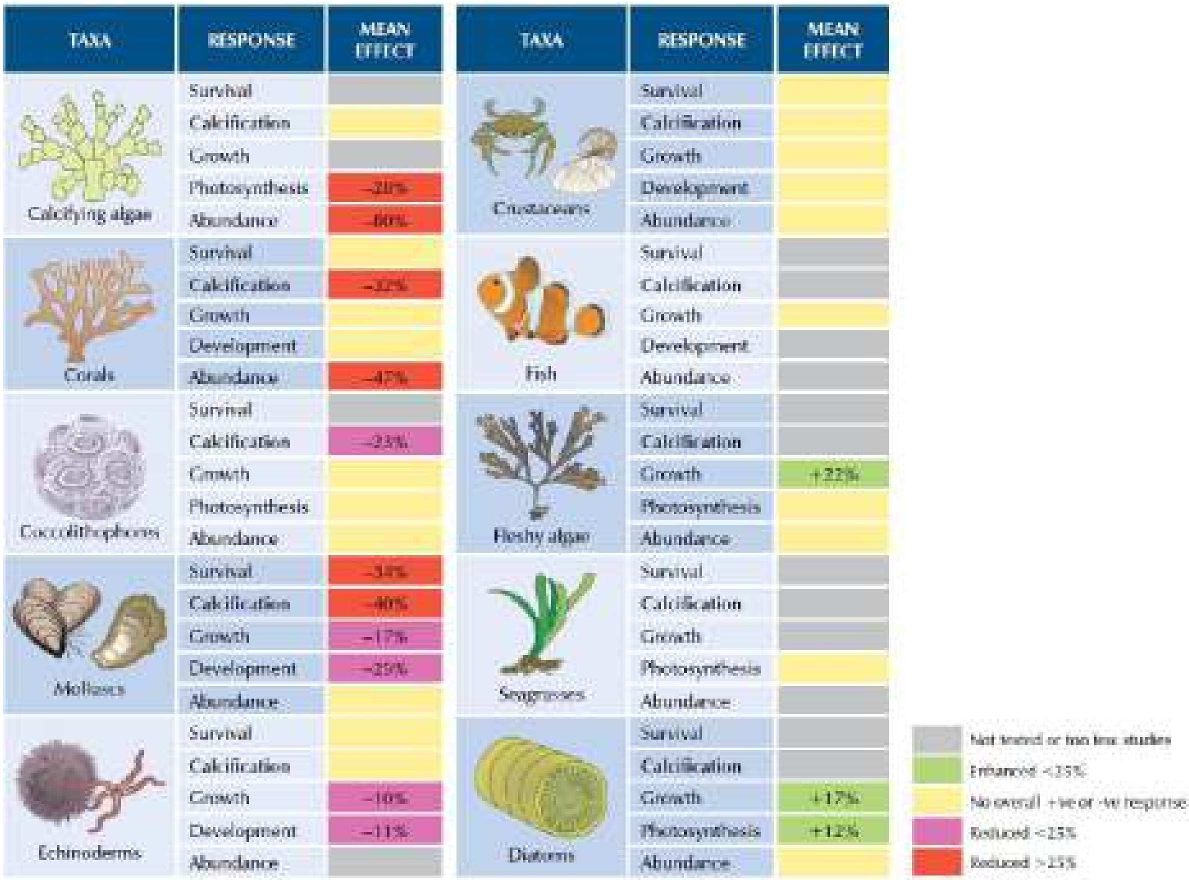
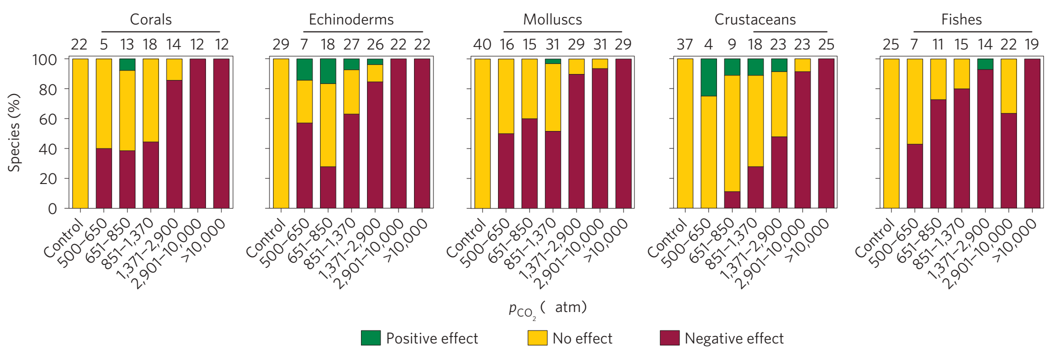


Figure 2. Sensitivities of animal taxa to ocean acidification (from Wittmann and Pörtner, 2013).



Local data on the impacts of other stressors (such as rising sea surface temperatures, pollutants, fishing pressure, availability of food for both cultured and wild species), and on the responses of key species to ocean acidification are deficient, making assessments of the impact of ocean acidification on local communities challenging. Nevertheless, the potential negative impacts of ocean acidification on coastal communities could be experienced through one or more of the following pathways:

• Reduction in food availability and food security at community, local and regional level.

• Changes to employment opportunities and incomes from fisheries and aquaculture – however this impact must be interpreted in relation to an existing long-term trend of labour exiting fisheries.

• Deterioration in marine recreation opportunities and appeal including those underpinning tourism.

• Loss of cultural values related to maritime and fisheries traditions, to resource management practices and to spiritual well-being, particularly in the case of indigenous communities.

• Social and cultural change resulting from declines in the fisheries economy and manifested through increased conflicts, increased illicit fishing activities, migration, unemployment and altered gender relationships as the traditional roles of men and women change.

• Disappearance, or stagnation of smaller and more isolated coastal fishing communities as outward migration reduces community size below the critical mass needed for provision of viable support services (e.g. schools, health clinics and transport links).

• Changes in trade flows and their related value chains.

• Responses, e.g. consolidation of ownership and control over productive capital (vessels, fish farms), leading to changes in income distribution in communities.

• Losses in the secondary economy, in areas such as boatbuilding, port services and sale of supplie.

• Loss of ecosystem services, such as coastal protection as reefs deteriorate.

• Lost efficiency through eroded levels of certainty in business investment.

In general, poor coastal communities, that rely heavily on harvesting or culturing species that are sensitive to ocean acidification, and that have limited alternative economic opportunities, are likely to be most vulnerable to the negative effects of ocean acidification. Fishing communities with robust fisheries and aquaculture governance regimes and management practices are likely to be more resilient.

Aquaculture production systems in which operators can exert significant control over water quality, food supply, or seed survival are likely to be more resilient, e.g. in the case of shrimp farming, integrated mariculture, or where fish cages can be moved to alternative sites (Hobday and Poloczanska, 2010). On the other hand, most capture fisheries and extensive mariculture that rely on wild seed are likely to be less resilient (Troell *et al.*, 2014). Impacts are felt through reduced or altered productivity of ecosystems and economically important species:

• All species and ecosystems have a 'tipping point' in terms of their resilience to ocean acidification and the impacts of multiple stressors. In the collapse of some species or ecosystems, ocean acidification can be envisaged as the 'straw that broke the camel's back', or the removal of the final supporting brick in the game of 'Jenga'.

• There is substantial evidence that some calcifiers (e.g., oysters and other bivalves) are particularly vulnerable to ocean acidification (Kroeker *et al.*,2013).

• Juvenile stages of many species tend to be quite vulnerable (Kroeker *et al.*, 2013).

• Coral reef fisheries are particularly vulnerable as the entire ecosystem is threatened by reduced abundance and vigor of corals and the calcareous algae that cement the reef structure (Hoegh-Guldberg *et al.*, 2007).

• Non-calcareous algae, such as seaweeds, may benefit but show a range of responses, often closely linked to other stressors and availability of nutrients (SCBD, 2014).

• In all cases, local context, impacts of other drivers and the ability of the dependent coastal communities to adapt and respond is critical.

Community responses to ocean acidification

Effective community responses to ocean acidification are likely to require an effective management of change, a process guided by long-term vision and leadership, to drive sustainable use practices, particularly when the benefits largely accrue outside short-term political cycles. Communities can be assisted in their responses in several ways, including by:

- Mainstreaming ocean acidification into climate change policies, plans and investment strategies at community and national levels (rather than creating additional new and separate responses);
- Raising knowledge and awareness of ocean acidification impacts and responses to inform policies and plans and to prioritise actions and investments;
- Building resilient and sustainable fisheries and aquaculture, including through reduction of ocean acidification and non-ocean acidification stressors (e.g. reduction of CO_2 emissions or pollution), supporting diversified coastal community economies and livelihood options, through community empowerment and community engagement in fisheries co-management;
- Accessing climate finance to (re)build 'blue carbon' sinks, such as mangrove forests, to explore possible local ocean acidification mitigation measures, or to 'seed' corals which show more resilience to ocean acidification;
- Fostering public and private investment in social, economic and environmental capital, particularly in communities and regions considered most vulnerable to the negative overall impacts of ocean acidification and other stressors, including in strengthening leadership and capacity in producer and community organisations.

Examples of possible responses in capture fisheries include:

- Improved management of coral reef fisheries, including recreational fisheries, e.g. through networks of marine protected areas, through community-based management, or reinforcing community-level rights over fishing and aquaculture;

- « Greening » of fisheries subsidies, for example, by redirecting fuel subsidies to support initiatives to reduce fishing pressure and rebuild fish stocks;

- Initiatives to add local value through fish processing, through development of niche markets, or through recreational use of fishery resources;

- Use of polyvalent fishing vessels using a variety of fishing gears to switch target species.

Examples of possible responses in mariculture include:

- Supporting seed availability for closed cycle mariculture to reduce reliance on wild seed, or moving vulnerable seed production to 'safer' areas;

- Selection of resilient species and culture systems, such as through integrated multi-trophic mariculture (e.g. in association with algae); through use of recirculating sea-water production systems, or ponds, such as shrimp or milkfish ponds, where water quality can be monitored and controlled;

- Use of selective breeding to improve resilience of cultured species;

- Development of monitoring and early warning systems for harmful algal blooms, ocean acidification and other stressors, and preparation of associated response plans;

- Improved spatial planning, coastal zone management and conservation of carbon sinks.

Lessons from other environmental change processes

Community responses to ocean acidification can be informed by a wide range of lessons from other environmental change and disaster responses. Coral bleaching events promoted the establishment of marine protected areas (Salm and Coles, 2001), species resilience and mapping studies. Fisheries collapses generated reforms and fishing effort reduction programmes (Da Rocha *et al.*, 2012), ecosystem approaches to fisheries, evolution of co-management regimes and enhanced community engagement and empowerment. Common concerns on sea-level rise fostered international coalitions of Small Island Developing States while tsunamis, cyclones and coastal flooding disasters underpinned disaster response plans, coastal offsets, conservation of natural coastal barriers such as reefs and mangroves. Common concerns over biodiversity losses, dead zones and illicit fishing generated CITES listings, market and trade measures, international monitoring and enforcement measures. Climate change mitigation and adaptation initiatives have already created new financing tools, green growth initiatives, codes of sustainable industry conduct and private sector innovations. In solving these challenges, many lessons have emerged on how to manage the change process – a political economy of change. These lessons provide guidance on how to raise political will ensure coherence in public policy, effectively deploy public finance and offset the negative impacts of change at national and international levels.

Recommendations

- Reinforce the climate change mitigation agenda with greater emphasis on ocean acidification particularly so that ocean warming and acidification are considered together.
- Improve awareness and knowledge at all levels, including on ocean acidification science, on the costs and effectiveness of adaptation and mitigation actions, and disseminate knowledge of lessons and best practices.
- Mainstream ocean acidification into national, regional and global policies, plans and investment strategies for climate change, for oceans, and in fisheries, aquaculture and coastal management.
- Improve ecosystem and community resilience, in particular through effective fisheries and aquaculture management, restoration of fish stocks and biodiversity and empowerment of vulnerable communities and groups (e.g. women, isolated island communities and indigenous coastal people)
- Finance a suite of actions in support of ecosystem and community resilience for vulnerable communities to improve and integrate approaches to adaptation and local mitigation
- Support and extend initiatives to monitor ocean acidification and linked stressors, particularly for vulnerable coastal communities and with respect to regions and countries where monitoring of ocean acidification is absent or deficient.

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Context

• Coral reef related tourism encompasses a broad range of recreational activities including diving, snorkelling, free-diving, education, cultural activities, fishing gleaning, kayaking, surfing, viewing from glass-bottomed boats, beach activities, and passive appreciation of beautiful coastal vistas (Cesar *et al.* , 2003; Hoegh-Guldberg *et al.*, 2000). Taking a very broad perspective, the values that people hold related to the existence of coral ecosystems unrelated to any direct use may also be considered. Reef related tourists and recreationists are diverse and can be from coastal communities living near reefs, other regions of the countries in which coral reefs are located (domestic tourists) or from distant countries (international tourists).

• The global value of coral reef based tourism in 2010 is estimated to 11.5 billion USD, and is expected to grow rapidly (Burke *et al.*, 2011). Dive tourism is increasing 20% a year, four times faster than global tourism (Cesar *et al.*, 2003).

• More than 100 countries and territories benefit from tourism associated with coral reefs, in 23 of these, reef related tourism accounts for more than 15% of gross domestic product (GDP) (Burke *et al.*, 2011).

• Alongside these macroeconomic figures, many micro studies exist that give concrete examples of the importance of coral reef based tourism to coastal communities:

– Around 2.5 million visitors a year enjoy the tropical coast area of Egypt of which 23% come specifically to dive and a further 33% participate in snorkeling activities (Cesar *et al.*, 2003).

– The Great Barrier Reef Marine Park attracts about 1.9 million visits each year and generated 5.4 billion AUD in tourist revenues and around 60,000 jobs in 2007 (Deloitte Access Economics, 2013).

– Annual net benefits of coral reef related tourism were estimated to 2.7 billion USD in the Caribbean, 258 million USD in Philippines and Indonesia, between 143 and 186 million USD in Belize, 100 million USD in Guam and 371 million USD in Hawaii (Burke *et al.*, 2011).

– The French Initiative for Coral Reefs (IFRECOR) is currently conducting the evaluation of ecosystem services provided by coral reefs in the French overseas territories. The total number of users (local and international) of coral reefs is estimated to 780,000 persons representing an average of more than 40% of the total number of tourists in the French overseas territories. Among these, 190,000 are divers, 517 companies are directly related to coral reef tourism, generating around 1,350 direct jobs. The total value of tourism activities supported by coral reefs is estimated to be approximately 183 million EUR for New Caledonia, Martinique, Guadeloupe, St-Martin and Moorea in French Polynesia.

Potential impacts of ocean acidification on coral reefs

• Corals are ecosystem architects, i.e. they provide the hard substrate and structure and hence habitat and niches for a unique ecosystem (Wild *et al.*, 2011; Dove *et al.*, 2013). Losing the 'architect' means losing the ecosystem. Coral reefs support approximately 33% of marine biodiversity (Reaka-Kudla, 1997). It will be almost impossible to predict in which order and how fast the biodiversity will degrade.

• Coral reefs are particularly vulnerable to environmental change (Fabricius *et al.*, 2007; Hoegh-Guldberg *et al.*, 2007). There is now abundant evidence that relatively small changes in temperature (which result in coral bleaching and mortality) and ocean acidification will lead to decreasing rates of calcium carbonate production, while rates of bio-erosion and dissolution increase (De'ath *et al.*, 2012; Dove *et al.*, 2013). There is also growing evidence that the vulnerability of some reef-building corals to thermal stress increases under ocean acidification. Furthermore reduced grazing activity by sea urchins and fish may lead to seaweed dominance (Hughes, 1994; Hughes *et al.*, 2010). One of the important take home messages from recent literature on these impacts is that ocean acidification is almost certain to affect a very broad range of physiological processes in marine organisms (Pörtner *et al.*, 2014). We are very likely only seeing the tip of the iceberg in terms of the fundamental changes that will occur within the ocean (Hoegh-Guldberg *et al.*, 2014; Pörtner *et al.*, 2014).

• Some of the evidence is very compelling. Based on 2258 surveys on 214 reefs from the Great Barrier Reef (GBR), there has been a loss of 50.7% of initial coral cover since 1985. Over a 16 year period in two regions of the GBR a decrease of 21% of the rate of calcification has also been demonstrated (De'ath *et al.*, 2012).

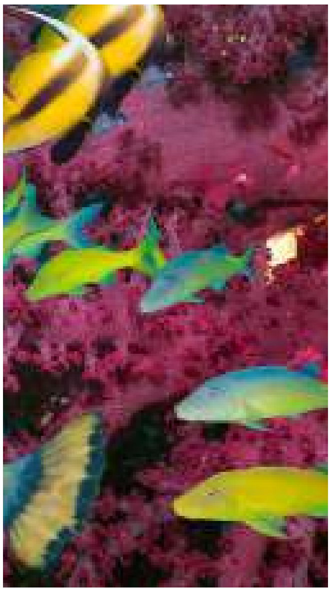
• Ocean warming and acidification in conjunction with other climate impacts (e.g. stronger storms, coastal droughts, increasing sediment run-off) are very likely to drive reduced reef complexity and biodiversity, reduced coastal protection, and a range of other fundamental impacts, e.g. disruption to larval development and physiology (Pörtner *et al.*, 2014). These changes could drive ecological shifts in directions away from structurally complex reef systems toward simplified ecosystems. Some coral studies even suggest an almost total disappearance of coral reefs around 450 ppm. (Veron et *al.*, 2009).

• Shifts in reef structure and composition as well as loss of ecological services and functional groups make reefs difficult to manage as a natural resource as they may become an unstable, unpredictable environment (Marshall and Schuttenberg, 2006).

Coral reef loss—consequences for tourism

• The loss of coral reefs is likely to make destinations providing reef-related tourism less attractive and result in a decline in tourist visits. The associated economic impacts will be reductions in revenues and profits for businesses that provide tourist services (e.g. dive operators, hotels, resorts, restaurants, transport) and employment for people working in the sector (Hoegh-Guldberg *et al.*, 2000). The severity of the economic impacts on coastal communities will depend in part on the diversity of the local economy and on the availability of opportunities in other sectors.

• The economic consequences of the loss of coral reefs also includes a decrease in welfare for tourists in terms of their enjoyment of reef-related activities (Amelung *et al.*, 2007). This component of the economic value of reef related tourism does not necessarily accrue to local coastal communities, but can be substantial and offers a potential source of finance for conservation efforts.



• How different types of tourists will respond to the loss of coral reefs is largely unknown. Some tourist activities are arguably more sensitive to changes in the state of coral reefs than others. It is expected that tourism for the purposes of coral ecology education, which ultimately relies on features associated with 'genuine' ecological experiences, will be more sensitive than recreational diving, snorkelling, and viewing, which in turn are likely to be more sensitive than beach activities. Even beach tourism will be affected in the long term if the quality and/or quantity of beaches are impacted, since many beaches are protected by reefs or formed from coral material.

• Tourism in coral reef regions is also likely to be affected indirectly due to the loss of coastal protection provided by the reefs. Tourist infrastructure on the coast (e.g. resorts, roads, airports) may face increased risk of storm damage and therefore disruption of tourist activities (Amelung *et al.*, 2007).

• A drop in tourism may result in the loss of support among coastal communities for marine conservation and marine protected areas (MPAs) if they no longer receive tourism benefits from such investments.

Community response and adaptation potential

Given that there is already considerable ocean acidification 'baked' into the world's oceans, it will be important to explore opportunities to help human communities adapt to ocean acidification. There are a number of potential opportunities to help coastal communities adapt. These opportunities are not at the global level of halting or reversing the impacts of ocean acidification. They are rather small-scale, local opportunities to support communities in their efforts to cope with the impacts of ocean acidification on tourism activities:

– *Modify conditions surrounding coral reefs.* There may be a range of opportunities for modifying the water chemistry of affected ecosystems such as coral reefs through engineering as well as biological interventions. One opportunity may be to actively encourage the growth of sea grass, which will reduce the amount of carbon dioxide through photosynthetic processes by day (Unsworth *et al.*, 2012). There may also be opportunities to actively pump water with low amounts of carbon dioxide or to directly apply alkaline materials in order to modify the local temperature and chemistry. These opportunities are currently being explored (GBRF, 2014). Local communities can also reduce the impact of coastal development (e.g. hotels, port facilities) close to the reefs, as well as reduce the impact of tourists by training reef visitors and/or restricting numbers. In the Red Sea, overpass bridges have been built to allow passage of swimmers and boats in order to avoid the destruction of the reef close to the shore. Deforestation and disruption to river catchments should be reduced in order to reduce sediments and nutrients inputs to coastal waters.

– *Building reef resilience.* Ocean acidification has the potential to reduce the ability of coral reefs to recover after disturbances such as cyclones, crown of thorns starfish infestations, and other episodic events by slowing the calcification and growth rate of corals and other reef calcifiers (De'ath *et al.*, 2012). In order to give coral reefs the best chance of recovering after these events, it will be important to reduce the influence of other local stress factors such as declining water quality, high sediment loads, overfishing and the direct destruction of corals by human visitors (Fabricius *et al.*, 2007; Hoegh-Guldberg *et al.*, 2007; Marshall and Schuttenberg, 2006). In this regard, it will be important to expand the use of marine spatial planning to create marine protected areas, while at the same time increasing the management of coastal catchment systems so that the movement of nutrients and sediments into local areas is reduced (e.g. preserving sea grasses and mangroves (Hughes *et al.*, 2007).

– *Broadening opportunities for coastal communities.* The development of tourism attractions in lieu of those based on healthy reef systems may be a viable adaptation. For example, Yucatan has developed underwater sculpture gardens that divers can enjoy (Decaires-Taylor, 2012). Cultural tourism, green tourism, and health related relaxation may be important alternatives in addition to nature-based tourism.

– *Innovative financing for adaptation.* Tourist taxes, user fees, public-private partnerships (Hoegh-Guldberg *et al.*, 2013), international financing, and sponsored ways to improve the management of coral reefs should be explored, especially in poorer countries. Opportunities for people around the world to adopt a reef may represent another opportunity in this regard. Building better networks, as well as knowledge and solutions platforms, will also improve the capacity of coastal communities to maintain the ecological resilience of their reefs. Simple strategies include encouraging local universities to involve students in reef protection by internship opportunities to get them to be stakeholders in future preservation.

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3. MODELLING AS A TOOL TO EVALUATE BIO-SOCIO-ECONOMIC IMPACTS OF OCEAN ACIDIFICATION

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The role of modelling in addressing the impact of ocean acidification on coastal communities

Modelling of the biophysical, economic and social components of coastal systems can provide essential input to the development of policy and management strategies for ocean acidification impacts. Specifically, the development, and use of models and of model results can inform the following stages of the adaptive policy/management cycle:

• *Issue identification and diagnosis* through prediction of impacts on marine systems, and dependent economic and social systems. This involves predicting the effect of ocean acidification on marine ecosystems and the availability and quality of ecosystem services, and the consequent effects of these changes on social wellbeing, for likely ocean acidification scenarios. The total cost of ocean acidification on vital market (protein and tourism) and non-market (biodiversity and storm protection) services, and on the structure and functioning of social ecosystems can be calculated. Models can further assist in highlighting regions/communities where impacts will be of greatest consequence, that is, where vulnerability to ocean acidification is greatest.

• *Evaluation* of alternative policies, and the development of adaptation strategies and pathways. Importantly, in this context, they can identify the distributional consequences of alternatives across individuals, stakeholder groups, and geographical and temporal scales, thereby highlighting potential conflicts.

• *Implementation* of alternatives by highlighting trade-offs, social learning, communication, engagement and capability building. Importantly, they can support conflict resolution by helping to develop common system understanding and definitions of impact pathways, and recognition of differences in stakeholder values and goals.

• *Assessment* of effectiveness or 'adequacy' of policy/management/adaptation actions, allowing for continuous updating of knowledge and system understanding, and for changes in social and economic institutions and values.

Additionally, at the community scale, models can provide a platform to help bridge the gap between knowledge production and it's use for decision making and action by acting as:

• Knowledge creators, by building awareness of the impacts of ocean acidification and its implications for societies;

• Knowledge unifiers, by creating a common understanding of knowledge on ocean acidification;

• Facilitators in the attribution of the impacts of ocean acidification. They can also be used as decision support tools, improving operational decision-making of local resource and environmental managers and, by enabling businesses to develop, evaluate and prioritize actions, increasing profitability and resilience.

Current modelling activity

With relatively few exceptions, the use of models to inform the development of ocean acidification policy or to inform adaptation pathways is rare (Blackford, 2010; Pandolfi *et al.*, 2011; Griffith *et al.*, 2012). Here, we provide a brief overview of areas of existing model development and use.

• Modelling of the chemistry of ocean acidification at the global scale is well advanced. There is relatively little uncertainty about surface-ocean acidification from ocean uptake of CO_2. (Orr *et al.*, 2005; Doney *et al.*, 2009). Regional differences in rates of acidification are identified (Thor and Oliva, 2015; Mongin and Baird, 2014) and uncertainty is mainly in IPCC emission scenarios. International efforts are now aimed at increasing global model resolution to better resolve coastal regions and to provide boundary conditions of regional models (Palmiéri *et al*, 2015; Queirós *et al.*, 2015).

• Broad hypotheses on changes in abundance of exploited species due to ocean acidification, some based on population dynamics or ecological models, have been used in conjunction with pre-existing bio-economic models to trace the impact of acidification on the scale and economic performance of commercial fisheries, or level of marine protein supply, in local communities. Such modelling has also sometimes considered distributive issues (across communities, gear types, etc.) and/or downstream economic impacts (Griffith *et al.*, 2012; Flynn *et al.*, 2015).

• Some modelling of the socio-economic impacts of ocean acidification has been done, focusing mainly on the study of the most vulnerable ecosystems (coral reef) or species (shellfishes) or where there are strong links to commercial or livelihood concerns (e.g. fisheries, aquaculture, tourism) (Brander, *et al.*, 2012; Cooley *et al.*, 2012; Mathis *et al.*, 2015) . Ranking of countries or places according to their vulnerability is an ongoing task supported by impact/risk or vulnerability modelling work (Mora *et al.*, 2013). Different frameworks, assumptions and data sets are used making the development of broad policy and management conclusions based on meta-analysis of such studies difficult. While some studies focus on vulnerability to the acidification hazard alone, others consider risk or vulnerability resulting from a combination of stressors (Mathis *et al.*, 2015; Cooley *et al.*, 2012).

• Compared to many other areas of environmental change, there are few studies of the monetary value of the loss of non-market ecosystem services (such as biodiversity, recreational fishing, culturally valuable species) due to ocean acidification. There has been some modelling work to provide estimates of the monetary values of the service rendered by the oceans to humans through carbon strategies (Herzog *et al.*, 2003)

In summary, while modelling of the chemistry of ocean acidification through CO_2 uptake and of the direct effects on some key commercial habitats and species is reasonably well advanced, modelling of the impacts of ocean acidification on other components of marine socio-ecological systems, and of the ecological and human behavioural processes, including feedbacks that may modulate the effects of ocean acidification on biota that drive these impacts, is very limited. We also note a general focus, to date, on global rather than regional and community scale modelling; on modelling of physical and biological processes and impacts rather than those that occur in human systems, and on modelling that represents multi-, rather than inter- or trans- disciplinary efforts.

Priority areas for modelling development to better address ocean acidification

While recognizing the need to build upon areas of existing modelling, here we identify urgent modelling needs in five key areas:

- A focus on marine socio-ecological systems and community-scale adaptation requires understanding of the processes of ocean acidification in coastal marine environments, and of the pathway to impact on coastal species and ecosystems (Hofmann and Schellnhuber, 2010; Hofmann *et al.*, 2013; Field *et al.*, 2014; Riebesell and Gattuso, 2015). However, while the open ocean chemistry and processes are well understood, it is at a coarse scale. Gaps still persist on ocean acidification's impacts to coastal ecosystems and communities (Ekstrom *et al.*, 2015; Hilmi *et al.*, 2013; Kroeker *et al.*, 2010; Godbold and Calosi, 2013). As a consequence, the applicability and transferability of these open ocean models and/or model results, to the assessment of processes of ocean acidification in coastal marine environments is limited (Haigh *et al.*, 2015; Gattuso *et al.*, 2014; Duarte *et al.*, 2013; Cooley *et al.*, 2012). Furthermore, the complexity of the physics due to the geomorphology and its openness to inputs from the land and the continental shelf, present additional challenges to developing physical and chemical models for the coastal zone (Duarte *et al.*, 2013; Aufdenkampe *et al.*, 2011). There is a need for integrated coastal models to capture the land-sea continuum and coastal open sea continuum.

- Attempts to assess the impacts of ocean acidification on biological communities using ecosystem models that include foodwebs and feedbacks are still in their infancy (Haigh *et al.*, 2015; Riebesell and Gattuso, 2015; Dupont and Pörtner, 2013; Branch *et al.*, 2013; Le Quesne and Pinnegar, 2012). There are substantial gaps in the knowledge needed to predict the biological, chemical, and ecological impacts of acidification, and direct cascade effects in the food web or indirect impacts through modification of habitat (Hofmann *et al.*, 2013; Narita *et al.*, 2012; SCBD, 2014; Gattuso *et al.*, 2014). Biodiversity and abundance of different groups and key species, of commercial or cultural value, are likely to be affected but the changes in community composition are highly unpredictable and remain unknown (Hilmi *et al.*, 2013; Cooley *et al.*, 2012). This is because different ecological paths, the variability in sensitivities and adjustments to ocean acidification (Kroeker *et al.*, 2010; Wittmann and Pörtner, 2013; SCBD, 2014), and the adaptive response of fishing and aquaculture practices— and other key drivers which depend on many factors (cultural, economic, technological, and institutional)— are challenging to model (Cooley *et al.*, 2012; Le Quesne and Pinnegar, 2012). In addition, there is a high concentration of single studies on crustacean, echinoderms, and mollusks to the detriment of more holistic ecosystem approaches that consider commercially significant non-calcareous species (Hilmi *et al.*, 2013, 2013; Riebesell and Gattuso, 2015; Godbold and Calosi, 2013; Branch *et al.*, 2013; Munday *et al.*, 2010; Doney *et al.*, 2009). Both theoretical/framework models of different types of coastal ecosystems and empirical models calibrated to local and community level conditions are needed (Haigh *et al.*, 2015; Riebesell and Gattuso, 2015; Griffith *et al.*, 2012). While empirical models do not necessarily need to be very detailed, they should be designed with a capacity to be fed by observational data to efficiently address changes in community composition and fishing pressure.

• The imperative to inform policy-makers of the likely economic and social cost of ocean acidification, particularly in areas most immediately vulnerable, will continue to be strong and models of social and economic impacts need to be further developed (Ekstrom *et al.*, 2015; Moore, 2015; Hilmi *et al.*, 2013; Field, 2014; Cooley *et al.*, 2013; Narita, *et al.* 2012). The economics of commercial sectors likely to be strongly impacted by ocean acidification should be further modelled along the lines mentioned above—bio-economic models in fisheries and aquaculture, economics of tourism, that adjust for ocean acidification and climate change (Cooley and Doney, 2009). Models should explicitly address interactions and synergies between the human and ecological systems (Griffith *et al.*, 2013; Le Quesne and Pinnegar, 2012). The overall structure of local/regional/national economies must also be considered when there is high dependency on fishery, aquaculture, and recreational sectors (Cooley and Doney, 2009; Doney *et al.*, 2009; Hilmi *et al.*, 2013). Economic and other social impacts, as well as adaptive capacity, should be studied at the individual, community, and country levels particularly in places where livelihoods depend on the availability and access to natural resources and where alternative opportunities are limited, not only as a source of income but also for protein or material supply (Cooley *et al.*, 2012; Allison *et al.*, 2009). A strong focus on models which can be used to predict long-term impacts and costs of ocean acidification on non-market ecosystem values, particularly biodiversity, is essential given the potential magnitude and irreversibility of changes (Cooley and Doney, 2009). The costing of alternative mitigation or adaptation strategies is also an important component to be modeled to inform policy and the prioritization of adaptation and mitigation actions.

• Societal action is generally more likely to be precipitated by events that are the realization of risk, as has happened with coral bleaching. However, anticipation through awareness raising and preparedness are important components of the capacity to cope and to adapt (Field *et al.*, 2014). Awareness is generally not raised through one-way science communication to the public and to decision-makers, but through actions that are directed to gain traction in the mitigation of ocean acidification vulnerabilities and CO_2 emissions at smaller scales such as local, jurisdictional, and state governments (Turley and Gattuso, 2012; Kelly *et al.*, 2011). Participatory policy, research, and modelling practices that engage the various stakeholders, decision-makers, managers and group representatives from the outset in OA risk analysis and vulnerability assessments of local conditions and needs are likely to improve readiness, and adaptive capacity (Field *et al.*, 2014; Perry *et al.*, 2012; Cooley, 2012; Weichselgartner and Marandino, 2012). Different kinds of models (i.e.: qualitative and quantitative, conceptual and numerical, for visualization only, for multi-criteria assessment, etc.) may be used to facilitate a rich two-way science-policy communication process that is both collaborative and integrative in its nature (van der Molen *et al.*, 2015; Makino and Sakurai, 2014; Charles, 2012; Pohl, 2008). Models can condense and synthetize information, serve as frameworks for future research, or they can be used to develop narratives for participatory foresight based on scenarios. Models and scenarios can take into account alternative pathways of ocean acidification impacts on ecosystem structure, functions, services and well-being or alternative behavioral or policy responses. In some cases, such as coral reef degradation, a wide range of impacts can be considered beside those on marine organisms, particularly where biodiversity/conservation concerns may be the primary policy driver.

• As modelling of ocean acidification moves from predicting the extent of ocean acidification due to the uptake of CO_2 to focus on biological and ecological, and social and economic impacts, there is also a need to broaden the focus of models to include multiple interacting climate-related and other drivers (Ekstrom *et al.*, 2015; Haigh *et al.*, 2015; Riebesell and Gattuso, 2015; Harvey *et al.*, 2013; Hofmann and Schellnhuber, 2010). In a similar manner, increasing the scope of models to include multiple competing sectors and a non-linear treatment of relations among components (Hilmi *et al.*, 2013), will improve the relevance of the models for policy purposes, particularly spatial planning.

Capacity constraints

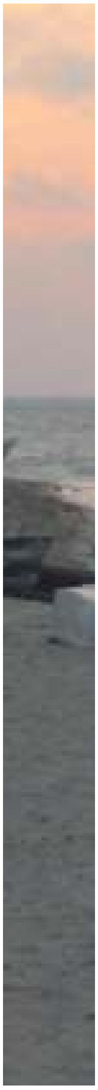
Model development and use are typically resource intensive activities, and given resource constraints there will always be the need to prioritise modelling needs. Globally, however, resource limitations will be less constraining where modelling occurs within an environment of coordination and collaboration rather than siloed efforts that only come together at the end.

• While many solutions will be designed and implemented at the local level, and supported by appropriately scaled models, there is a strong need for sharing of knowledge, expertise, and data. Mechanisms for data sharing will be particularly important as access to experimental/field data across the biological and social sciences are required to inform and calibrate model development.

• The need for a stronger focus on participatory modelling practices (Sandker *et al.*, 2010; Jonsson *et al.*, 2007) that support knowledge creation and unification at the community level, and for policy-relevant models both require greater emphasis on the role of effective communications. This suggests an important role for 'knowledge brokers' and ocean acidification champions, both of whom will need to be empowered to act as translators. NGOs may play an important role here as can *ad hoc* groups such as the Washington State Blue Ribbon Panel (Washington State, 2012).

• While not unique to ocean acidification, modelling of socio-ecological systems requires interdisciplinary approaches to support proper system-level knowledge creation and understanding (Armitage *et al.*, 2009; Liu *et al.*, 2007). The challenges to effective interdisciplinarity are well known and it will be important that the next generation of modellers be equipped with the skills required to operate effectively in this environment.

• Capacity constraint depends on the availability of programming skill. Much of the skill and workforce is connected to the information technology sector (Google, Facebook, Amazon, etc.). Exploration of public – private partnership should be advanced to bring this resource forward in the socio-ecological modeling aspects of ocean acidification.



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4. POTENTIAL SOCIETAL ACTION AND ADAPTATION

Libby Jewett (chair), Sarah Cooley (facilitator), Dan Laffoley (facilitator), Caroline Hattam, Hina Grepin, Linwood Pendleton, Hans Poertner, Samir Maliki

Context

The following sections highlight key messages and actions that arise from an analysis of potential societal actions and mitigation options related to ocean acidification impacts. First and foremost, there is a pressing need to sustain and increase actions to address the root cause of ocean acidification— stemming the rising levels of carbon dioxide in the atmosphere — as well as caution that a dependency on geoengineering solutions may not hold many, if any, viable solutions. The group's analysis concluded that a number of common obstacles exist to taking increased action regardless of specific sectoral needs and requirements. It is evident that a suite of actions could be instigated to improve local ecosystem health and resilience and thereby lessening the potential for impacts from ocean acidification or delaying the full impact of ocean acidification. There are other impacts (a few examples are given) which may require broader scale adaptation responses with associated costs. Partnerships between various sectors (industry, research, foundations, coastal communities) and innovative methods to encourage adaptation were explored (see Table 1).

CO_2 mitigation

Alongside the adaptation agenda for ocean acidification there is a compelling need to sustain and grow arguments for significant and urgent reductions in anthropogenic carbon dioxide emissions to tackle ocean acidification. This should stem from local and regional stakeholders being informed about the challenges of ocean acidification at local and regional scales, set within the overall context of combined climate associated hazards contrasting futures for ocean and society from different anthropogenic CO_2 emissions scenarios (Gattuso *et al.*, 2015), storm events, sea level rise, warming that may exacerbate or be exacerbated by the effects of ocean acidification. They should consider how the associated impacts evolve with various degrees of ocean acidification. Greater traction may be gained at the political level by identifying nations and states that face the earliest risks from progressive acidification and bringing them together to consider new risks they may be exposed to at the coast from acidification. Such an approach will ultimately lead to personal, business and industry-related views about levels of tolerance for the transition to dangerous climate change including ocean acidification once a critical threshold is surpassed for ecosystem may also exceed the human capacity for suitable adaptation. Affected citizens might be then motivated to express their concerns and conclusions to local, regional and national policymakers with the intention to influence the national contribution to emission reductions, and the UN level discussion of climate targets to influence long-term global goals. Creating such an alliance of like-minded countries, states and stakeholders is also fundamental to creating greater adaptation action in the post 2015 agenda, for identifying common research needs but also sharing the fact that mitigation action now will reduce adaptation costs later.

Key message - Sustained calls for significant and urgent reductions in anthropogenic emissions of carbon dioxide must continue to be the highest priority even though development of adaptation strategies are underway. Options for adaptations are limited and whilst these should be maximised, reducing the root cause – rising levels of carbon dioxide in the atmosphere – remains the primary goal.

Geoengineering

The discussion and broad agreement at the societal level on emission reductions and long-term global goals ultimately involves developing support for national contributions to geoengineering approaches. These are needed in a portfolio of emission reductions, and include technologies causing negative emission that would thereby reduce the degree of ocean acidification. Factoring in the need to address progressive ocean acidification demonstrates that some geoengineering proposals such as solar radiation management do not alleviate the continued accumulation of CO_2 and thus ocean acidification. In contrast, carbon dioxide removal techniques (mostly geological storage of CO_2 and underground storage of organic carbon, i.e. biomass) help ameliorate ocean acidification but need careful assessment of the benefits and trade-offs involved, such as growing biomass or CO_2 leakage and exposure. Many of the ocean-based solutions such as using ground-up olivine offer possibilities but are unproven at scale and may be accompanied by significant extemal costs. Hence the mitigation argument is reinforced.

Key message - Factoring ocean acidification into the geoengineering debate reduces options proposed to tackling climate change to just those that tackle the core issue of removal and/or reduction of atmospheric levels of carbon dioxide. Those geoengineering options that remain are unproven at scale and may be accompanied by such significant external costs (environmental, economic etc) that reducing emissions probably remains the most viable option.

Reduce local stresses on fish and corals so in order to decrease the impacts of ocean acidification

The effects of ocean acidification are compounded by other stressors. And on the top of that, ecosystems that are exposed to ocean acidification, in the midst of many stressors, may benefit from steps that reduce the effects of ocean acidification. Estuaries that support commercially and nutritionally important shellfish could withstand the impacts of ocean acidification better if nutrient pollution and riverine inputs were reduced (action that may require coordinated efforts by government, industries, and NGOs). This would require reducing nutrient inputs (from agriculture and sewage) into surface and groundwater. Reducing waste of fertilizer could represent an economic saving to local agriculture, but outlawing fertilizer use could put agriculture out of business. Reducing nutrient input from sewage could benefit human health and well-being as well as limiting ocean acidification, although economic costs, infrastructure development, and possibly education are needed to accomplish that.

Better land-based management could help coral reefs more effectively if sedimentation, nutrient pollution and overfishing are reduced (Burke *et al.*, 2011). Generally, healthy marine and coastal ecosystems may cope better with ocean acidification than degraded systems. Improving and protecting these systems (e.g. through restoration or marine protection) may provide double dividends from improved ecosystem service provision and increased ocean acidification resilience. Active steps could be taken to help the recruitment and proliferation of ocean acidification-resistant organisms (e.g. coral reef managers or restoration efforts, like those proposed by recent recipients of the Paul Allen Ocean Acidification Adaptation prize http://www.pgafamilyfoundation.org/oceanchallenge/, could adjust their efforts to focus on ocean acidification resistant species). Such actions may not maintain existing assemblages of taxa, but could help these ecosystems transition to more ecologically sustainable states that support existing ecosystem services. Of course, increased protection may also displace fishers adding to increased pressures on ecosystems outside of the protected areas. For more highly managed systems, like aquaculture, ecological mitigation could be undertaken (by industry) by better managing local circulation, co-managing shellfish and macroalgae, and changing the assemblage of organisms managed.

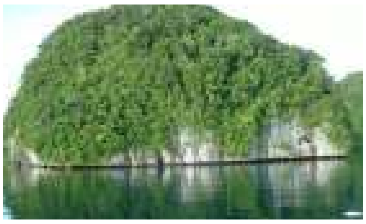
Key message - A portfolio of actions could improve local ecosystem health and resilience and thus lessen the potential for impacts from ocean acidification, delaying the full impact.

Obstacle: Reducing environmental stressors already has proven challenging in many areas where ocean acidification is likely to have greatest impact.

Common obstacles to adaptation of industry across sectors

Examination of progress on adaptation in different sectors exposed to the risk of ocean acidification reveal some common obstacles to greater uptake and action. Industries (fisheries and tourism, particularly) that may be touched by ocean acidification and climate change might be slow to put precautionary plans in place for a variety of reasons, including, but not limited to:

Lack of biological information - Nearly every review or plan summarizing the possible impacts of ocean acidification on human communities via changing ecosystem services mentions that there is not enough information from experiments on key economically or ecologically important species to develop more quantitative assessments (Ekstrom *et al*, 2015 ; Cooley *et al*, 2009). Until we understand which general mechanisms govern ocean acidification responses, the responses of organisms to ocean acidification will continue to be reported on a species-by-species basis and forecasts will be vague. The current level of information has not proven compelling for most industries to take precautionary action.



Lack of political awareness of inherent risks - Ocean acidification coupled with other stressors such as deoxygenation and ocean warming raises the risk at local and regional scales to the viability of coastal economies and underlying health of ecosystems and biodiversity. Unless connections are made between observations, science, and cultural and economic values, political action is unlikely to be taken until impacts are felt and when options for adaptation in vulnerable regions may already be reduced.

Lack of understanding of how ocean acidification is different from previous problems we have experienced - Human experience in tackling coastal problems has often focused on managing conflicts and resources, or in the case of episodic catastrophies (tsunami, hurricanes) by periodic requirement for significant aid and investments. We have not been faced with local to regional scale changes in ecosystem functionality. An obstacle to action is the lack of awareness that progressive ocean acidification will permanently (from the perpective of human lifespan) change seawater chemistry (Gattuso *et al*. 2015) ,and when impacts arise this time around we can't easily buy our way out of the problem.

Uncertainty in impact or timing - When impacts arising from increased risk are uncertain or not immediate, governments and industries have a variety of other everyday concerns to which they need to attend to. In the face of extreme uncertainty, industries are inclined to focus on things that are clear and actionable (Cooley *et al*., 2015). For example, U.S. fisheries management does not currently include climate change in fisheries management plans, as they are developed on the 2-5 year time scale, while climate change manifests on the 10+ year timescale (Cooley *et al*., 2015). More immediate concerns are typically addressed in fisheries management, especially because the uncertainty grows with the time horizon.

Unwillingness to acknowledge a problem and unclear path to solution - Coral reefs in many locations (e.g. Florida) are already quite degraded from warming, pathogens, and physical stressors (e.g. Reefs at Risk project; Burke *et al*, 2011). However, scientists working in these areas have noted the lack of interest of the local tourism industry to proactively acknowledge warming and acidification as problems. It seems that industry representatives don't want to admit that any problem exists for fear that would decrease tourism interest. And it remains unclear what action they should take if they do admit it.

Unclear cost/benefit of acting - Without improved estimates of the value of services currently obtained from ecosystems at risk from climate change and ocean acidification, business people cannot weigh the costs and benefits of acting sooner or later to future-proof their industry. Any kind of precautionary action carries costs, and because of human tendencies to discount future savings and/or costs, acting later always seems more appealing, particularly in an uncertain situation.

Lack of acute problem - **Most areas do not face acute catastrophes from climate warming and acidification. Generally, episodic events (like upwelling in the Pacific Northwest) will force the issue onto business-people's list of immediate concerns. Without "catastrophes" associated with warming and acidification, the urgency to act now is low.**

Lack of clear and scalable solutions - **There are few scalable solutions that communities and industries can adapt to reduce the impacts of ocean acidification.**

Exploration of several adaptation options

Ocean acidification impacts on coral reefs may lead to reduced shoreline protection from erosion and storm damage. Two key adaptation strategies are explored: armouring coastlines with manmade structures, and moving populations away from threatened coastal areas.

Armouring coastlines

Coral reefs protect thousands of kilometers of coastline and more than 13 million people living within one kilometer of reefs (Ferrario *et al.*, 2014). The need for shoreline protection may therefore exceed our ability to manufacture appropriate structures that can replace lost coral reefs. Locations for armouring may need prioritising (e.g. those adjacent to large populations) and creative solutions to armouring will need to be developed (e.g. the use of subway carriages). This will require partnerships between research, local authorities and business to identify and potentially manufacture appropriate armouring materials and to deploy them in the most effective locations. Local businesses, such as beach front hotels, shops and services may also be interested in investing in such protection, where able. The same may be true of insurance companies if artificial protection reduces future claims for storm/flood damage.

Key message - The construction of artificial infrastructure will require substantial economic investment and key areas may need to be prioritised (e.g. areas adjacent to large populations).

Moving vulnerable populations

Moving populations away from locations made vulnerable by ocean acidification-compromised coral may be a temporary measure (Barbier, 2015) (e.g. in response to extreme weather) or a long-term strategy (e.g. in response to catastrophic damage, continuing loss of coastal zones due to erosion or salt water intrusion). Some situations can be planned for in advance (e.g. storm evacuation strategies, movement of populations following shoreline management plans), whereas others may be in response to emergency situations (e.g. catastrophic damage to infrastructure) (Upadhyay and Mohan,2014). A key obstacle to such movement is often people's willingness or ability to move. Temporary evacuation requires effective strategies in which local authorities engage with the public to ensure messages are communicated, that transport and accommodation are available as well as essential resources such as food and water. The scale of this support will depend upon the damage caused by the extreme weather. Long-term migration of populations will require different strategies to avoid negative displacement effects, such as excessive demand for natural resources and increased conflict in locations where migrants settle, poverty and loss of livelihood opportunities, cultural clashes and political unrest (Gemenne,2010). Support needs to be given to both the displaced and the receiving communities. Partnerships will be needed between national and local authorities to identify appropriate receiving communities with opportunities for migrants. Funding from government and local authorities may also be required to support essential services and the development of new business/employment opportunities for both the migrants and the communities in which they settle.

Where effective insurance is available, insurance companies may play a pivotal role in helping people to return to locations affected by storm damage. They may also encourage migration where they refuse to offer insurance against flooding and storm damage.

The movement of people is associated with considerable costs. There is the "out of pocket" cost involved with the physical movement of people from one location to another. There are also social and cultural costs in terms of disruption to family and community ties, loss of social capital, and so on.

Key message - Moving vulnerable populations is an extremely costly action (social, economic and environmental) and to be effective will require considerable planning, community education and long-term commitment.

Fisheries

Technological and methodological innovations can help both wild harvest and shellfish fisheries adapt to future conditions in ways beyond simply delaying ocean acidification's impacts. New, resilient strains should be developed by selective breeding or genetic engineering, for raising in enclosed aquaculture systems or in unprotected coastal culture installations. Risks of raising non-native or genetically modified organisms include the possibility of escape into the natural environment, altering natural gene pools or releasing invasive species into new habitats (Muir, 2014). Innovative aquaculture techniques such as co-culture of photosynthetic organisms can be implemented to offset ocean acidification effects in enclosed aquaculture systems. Environmental monitoring (e.g. that in U.S. Pacific Northwest) has already been implemented to decrease day-to-day risks to aquaculture. In theory, these bioengineering technologies, once proven, could be transferred to less economically advantaged nations or companies (Barton *et al.*, 2015). In both of these types of adaptation, economic costs of genetic modification, selective breeding, or co-culture facility development could be quite high, limiting adoption of these options at first to those nations or companies that have significant economic resources. However, early adopters would benefit from earlier profitability and possibly "cornering the market". Although these methods also include dependence on costly coastal property, they might be implemented in an ecosystem management context to help improve water quality and manage ether nutrient pollution loads that exacerbate ocean acidification as well as ether coastal problems.

Key message - Adaptation options available currently for shellfish (protected aquaculture, etc.) are associated with significant economic costs that may limit their application to wealthy nations or corporations.

Adaptations directed at finfish harvests not focused on delaying the onset of ocean acidification (see above) center around improving management of the resource. "Preemptive" adaptation might involve reducing fishing pressure on all harvested species and relying less on fish harvests, in advance of documented damage from ocean acidification. The main disadvantage of this approach would be to put fishermen and allied industries out of business, with no guarantee that alternative livelihoods or protein sources exist. Other management-based adaptations could include switching to resilient species (once they are identified), switching fishing-based sectors of the economy to other sectors, or fishing in different territories. These actions could have disproportionate effects on women or specific age groups, or contribute to economic inequality in societies (see below) (c.f. French Polynesian young women shifting from clam harvests to coconut harvests, and losing income and social power; or how fishing farther away from ports tends to harm artisanal and subsistance fishers and not industrial or corporate harvesters). Losses of fishing opportunities due to ocean acidification could displace fishing pressure and can cause overfishing, conflict, or access problems if this involves new locations.

Key message - Adaptations available for finfish populations are largely preventive in nature now, and require strong management to implement. They also have potential to worsen inequalities that exist in fishing-reliant populations.

General overarching economic and human costs to the adaptations

The economic and human costs of adaptation will be decisive for the problem of ocean acidification. Each action must consider this cost in order to achieve this goal. The calculation of costs must concern the inequality of opportunity by taking into account the investments that generate profit in the short, medium and long term. Good cost control practices must be generalized. Research needs to include figuring out the costs of both marine ecosystem adaptation and human adaptation policies in order for the effect on the global economy to be known. The welfare implications of ocean acidification need to be measured in terms of changes in consumer and producer surplus rather than changes in gross revenue.

Key message - Act more directly on the consumer rather than the producer to get change in the consumption model.

Cultural impacts of ocean acidification

The impact of ocean acidification is not only ecological or economic but also social and cultural. For example, the loss of biodiversity may not only have consequences in terms of social structure or generational make up, but also from the point of view of gender. Scarcity of lagoon resources may affect specific population groups, such as women or young people, because activities are socially distributed. They may affect the balance of gender configuration inside families. This may result in migration, in departure of the youth population who must find other sources of income. An alternative would be to develop on-site economic activities, such as aquaculture, provided to develop financial and technical resources. Moreover, the loss of some species may affect the cosmological structure because fishes are not only a natural ressource (Grépin, 2006) but may be part of history of a clan, so their disparition affects the proper group identity.

Case study: On Tuamotuan island (French Polynesia), the lagoon is considered as a female area whereas the ocean is a male one. Men go towards ocean to fish, women go in the lagoon to take clams and shells, where clams are for eating and shells for doing artisanal activities. Ocean acidification and other parameters such as the warming of water temperature, impact the lagoon more than the ocean, so it affects primarily women and their resources. Young people also pursue activities in the lagoon because they have free access to it. The scarcity of clams pushes them to change activities, such as to copra farming, but it makes them dependent on the elders who own the land and its fruits. So changing to that activity is a big source of social tension. A viable alternative would be to develop aquaculture in order to keep women and youth and maintain the social balance in terms of gender and age. But this needs real interaction between the community and scientists to find the best place and methods in order to achieve simultaneous ecological and cultural resilience.

Key message - We cannot separate the natural and the cultural aspects because changes in the ecosystem have sociocultural implications. Ecological and social resilience must be addressed simultaneously in order to find a viable balance for the communities concerned.

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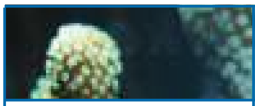
Adaptation changes and partnerships that might benefit adaptation:

	Aquaculturists (shellfish growers)	Shoreline protection from coral reefs	Wild harvest (mostly finfishers)
Behavior Change	Timing of activities. Liming/seeding with crushed shell (maybe G-I). Move operations	Enlist tourists in restoration. Reduce pressure on reefs (maybe F-I)	Change species territory, gear within legal, economic boundaries. Retain displaced workers.
Behavior Change Infrastructure investment	Build protected facilities. Add monitoring / forecasting capacity (G-R-I) Test/engineer resilient species (I-R)	Armour coastlines with artificial substrates; promote growth of resilient species (I, R, F)	Different gear/ boats to support behavior change (maybe R-I)
Loans	For refitting, researching, moving (G-I or F-I)	For seeding areas with coral; for seeding coral areas with seagrass	For gear switching (G-1 or F-I)
Tax Credits	For refitting/ researching (G-I)	If protection lost, credits to encourage people to move further from the coast (G-C)	With permit buyback scheme to reduce fleet size? (G-I)
Taxes	Tax consumer to fund research and tech development (G,R,I)	Tax consumer (tourists, coastal landowner) to fund coral reef protection (G,R,I)	Tax consumer to fund research and tech dev (G,R,I)
Insurance	Guard against bad years (like crop insurance) (G-I or I-I)	Reinsurance builds vulnerability into models which forecast shoreline vulnerability	Guard against bad years (like crop insurance) (G-I or I-I)
Prizes	Urge innovation on monitoring, resilience, refitting, etc. (G-I or F-I)	Urge innovative techniques for culturing resistant species and testing	Urge innovation on monitoring, co-management, fully sustainable fishing (G-I or F-I)
Risk pooling	Small-scale growers collaborate to protect hatchery or grow-out area, lime/seed flats, (maybe R-I)		

See annotations in table above. Parentheses and abbreviations indicate which types of partnerships may be needed to implement each activity. Abbreviations: Government (G); Industry (I); Research (R); Foundation (F); Coastal Resident (C). For example, «R-I» indicates research-industry partnership.

5. GOVERNANCE, GOVERNMENTS AND LEGISLATION

Alexandre Magnan (chair), Carol Turley (facilitator), Salim Al-Moghrabi, Louis Celliers, Jason Hall-Spencer, Paul Holthus, Kirsten Isensee, Eleni Papathanasopoulou, Laura Recuero-Virto

Context

The mandate for policy action on ocean acidification falls under the remit of the United Nations Framework Convention on Climate change (UNFCCC) since, like climate change, ocean acidification is a result of anthropogenic CO_2 emissions. The international community dealing with climate change must play a decisive role in encouraging national and local governments to scale-up efforts to mitigate CO_2 emissions thereby reducing the impact of both climate change and ocean acidification. The annual UNFCCC meeting, Conference of the Parties (COP) represent pivotal opportunities for the ocean science community to provide the international community dealing with climate change with information and recommendations leading to informed solutions and policy guidelines that address ocean acidification.

The objective is to develop a comprehensive message about the relevance of ocean acidification in current and future governance agendas. The target audiences include the international community dealing with climate change, climate negotiators, national leaders, UN agencies and Non-governmental Organisations, as well as the parties involved in the UNFCCC process.

Why is ocean acidification a governance issue?

•The ocean acidification problem is already happening, and represents a major threat to ecological and human systems

There is no scientific disagreement about the progress of ocean acidification (Hoegh-Guldberg *et al.*, 2014; Pörtner *et al.*, 2014). Rapid changes in ocean chemistry due to CO_2 emissions in the surface ocean and its serious consequences for marine life are well-established facts. Future impacts from ocean acidification and warming have been studied across the world and projected impacts will include food-web disruption in the Arctic, altered senses and behaviour by fish, loss of biodiversity, degradation of the Great Barrier Reef and major losses in aquaculture production (Howes *et al.*, 2015; Weatherdon *et al.*, 2015; SCBD, 2014). These negative impacts on the goods and services provided by marine ecosystems will affect society by threatening food security (UNEP, 2010; Huclscenbeck, 2012), coastal defences, tourism, as well as recreational activities (Armstrong *et al.*, 2012) and aesthetic and spiritual benefits. Additionally, the future ocean will face reduced capacity to absorb anthropogenic CO_2 emissions further reducing its ability to regulate climate. Thus ocean acidification threatens the very elements, such as basic materials for a good life, security from natural disasters, health benefits and appreciation of nature, which contribute to human well-being for current and future generations (Millennium Ecosystem Assessment, 2005)

The speed and strength of ocean acidification, and its subsequent impacts on marine and societal systems, is a compelling argument for the international community dealing with climate change to urgently commit to reducing CO_2 emissions well below the level needed to stop global warming at 2°C. The trajectory that would accompany an allowable 2°C global temperature rise would already cause irreversible loss of certain marine ecosystems and their services (Hoegh-Guldberg *et al.*, 2014; Pörtner *et al.*, 2014; Howes *et al.*, 2015; Gattuso *et al.*, 2015).

• Solving the problem requires international collaboration

International governance has a track-record in dealing successfully with water-borne contaminants (such as tributyltin, DDT, waste nutrients, radionuclides). Once the threats were clear, policies were designed to protect the marine environment and reduce pressures to coastal communities (e.g., agreements under the International Maritime Organisation, the London Protocol/Convention on waste dumping, the Stockholm Convention on the use of Persistent Organic Pollutants).

Ocean acidification is a global process with local impacts, e.g. on fisheries and coastal communities, so there is a need to act urgently at all levels : international, national and local. National and sub-national decision-makers need the support of the the international community dealing with climate change, as it can play a decisive role by (1) encouraging the responsible policy bodies and governments to scale-up efforts and (2) providing guidance. Ocean acidification is a cross-boundary issue as polluting nations/activities can affect marine ecosystems and people on the other side of the planet (Makarow *et al.*, 2009).

What can the international community do?

• ACTION 1: Include ocean acidification in governance and legislative plans

Ocean acidification is a threat to national growth and development, particularly in the developing nations, and should be reflected in national and subnational development plans. Therefore, a key objective for the international community dealing with climate change is to promote the inclusion of mitigation and adaptation to the impacts of ocean acidification and warming in policy relevant documents, international climate change regulation instruments and platforms (e.g. United Nations level, economic communities, regional conventions) with the aim of supporting national and subnational actors to improve coastal and marine governance (e.g. multi-sectorial legislative reforms). The following interventions are proposed for consideration:

- Encouraging regional conventions/platforms and economic communities to mainstream the reduction of climate change and ocean acidification in member country policies;

- Developing national and sub-national policies for mitigation and adaptation of CO_2 emissions and ocean acidification (Turley, 2005; Doney *et al.*, 2009);

- Mainstreaming ocean acidification into existing environmental and coastal management policy and legislation (integrated coastal management, environmental management, climate change, national to local economic development plans, blue-green/ocean economy strategy);

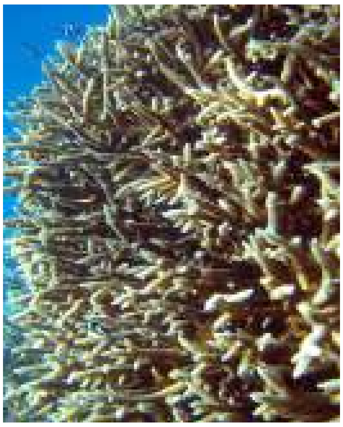
- Following the Rio+20 Conference, ocean acidification is now mentioned within the Sustainable Development Goals and indicators which can be used to track chemical and biological change have been developed to inform policy mechanisms;

- Creating a network of marine protected areas within a coastal and marine spatial planning framework that accounts for risks and vulnerability of climate impacts including ocean acidification;

- Providing policy mechanisms to promote restoration of marine habitats and seascapes;

- Developing feedback mechanisms between national and sub-national administrative levels as well as involving stakeholders;

- Encouraging the inclusion of ocean acidification indicators in national and regional state of the environment reports.



•ACTION 2: Build capacity and research in ocean acidification across the world and within nations

Knowledge about ocean acidification and its impacts on marine ecosystems exists, nevertheless expertise and capacity is not equally distributed globally. Thus, promoting and encouraging the building of scientific capacity worldwide should be one major goal of the international community dealing with climate change;

- Establish ocean acidification monitoring and observational capacity and stimulate the assessment and forecasting of vulnerability at various scales in order to identify "hotspots" of impacts that will require priority investigations, i.e. resource mobilisation, adaptation strategies and management interventions. Frameworks already exist such as the GOA-ON (Global Ocean Acidification Observing Network) and the OA-ICC (Ocean Acidification International Coordination Centre of the International Atomic Energy Agency, IAEA);

- Improve international collaboration, as well as capacity and technology transfer between nations and regions, to fill in knowledge gaps and facilitate ocean acidification activities;

- Enable the collection of and access to ocean acidification data, information and knowledge, scaled for different national and sub-national administrative levels;

- Empower regional, national and sub-national institutions, as well as the public-private partnerships and multi-stakeholder fora, to address climate change mitigation and adaptation to ocean acidification impacts;

- Establish ocean acidification as a priority in trans-disciplinary research agendas in order to increase knowledge about its consequences;

- Raise awareness and understanding of the risks of ocean acidification among the population through inclusion in national education agendas.

Recommended strategy

Seven specific and achievable recommendations are made to the international community dealing with climate change to support and direct its strategy in addressing ocean acidification:

1.NORMATIVE TEXT – Consider the impacts of ocean acidification in the context of UNFCCC negotiations

WHY: First, to acknowledge that the ocean is at the frontline of climate change and that ocean acidification is a major risk to society, which depends on a healthy ocean. Second, to stimulate mainstreaming climate change and ocean acidification into regional, national and sub-national policies and legislations.

2. FINANCE – Actively encourage the inclusion of "ocean-related" projects in the Green Climate Fund

WHY: To enable coastal and island communities to benefit from climate finance to adapt to ocean acidification and warming. Although the current framework of the Green Climate Fund allows ocean-related projects to be proposed, and given both the role of the ocean in climate regulation and the threats induced by ocean acidification, ocean-related projects should be specifically encouraged. It is however crucial, in parallel, that ocean acidification is mainstreamed into regional or national policies and research agendas in order to encourage the development of ocean-related projects.

3. PARTICIPATORY SOLUTIONS – The ocean scientific community especially, together with civil society and governments, should be involved in the assessment of adaptation and mitigation proposals

WHY: To enable an evidence-based assessment of how climate change-related solutions may impact (positively or negatively) the ocean and ocean acidification. It is important that the ocean scientific community is involved in supporting sound mitigation of and adaptation to ocean acidification actions happening on the ground, from the national to the local level, including regional cooperation aspects. We thus argue here for the integration of ocean scientists into projects' assessments mechanisms at the international level.

4. BLUE CARBON COASTAL ECOSYSTEMS – Promote the methodology and protocols to measure coastal blue carbon to include conservation and sustainable international financing of coastal ecosystems carbon sinks.

WHY: To use international governance mechanisms to protect and restore blue carbon sinks and maintain healthy coastal and marine ecosystems. A healthy ocean is indeed key to help "avoid the unmanageable" (e.g., mitigation of climate change and ocean acidification). It is also key to help "manage the unavoidable" (e.g. support adaptation and resilience of ecosystems, economic activities, and so on). In addition to international mechanisms, it is key to develop regional, national and sub-national policy tools and legislations that will allow for the financing of the protection and restoration of natural marine carbon sinks.

5. OCEAN OBSERVATIONS – Maintain ocean acidification observations in UNFCCC Subsidiary Body for Scientific and Technological Advice (SBSTA) documentation on systematic observations of climate change.

WHY: To ensure the development of ocean acidification observations, warnings and forecasts by countries, and for the benefit of the global community. This will also help get a global understanding of the key question: are we on the right track to mitigate against and adapt to ocean acidification?

6. CAPACITY BUILDING – Promote understanding of ocean acidification at influencer-level (e.g. national-level administrations or NGOs) but also raise awareness of ocean acidification as part of national education agendas in all countries.

WHY: To increase political motivation to act urgently and ensure that people involved in the design and implementation of policies have a good understanding of why new policies/legislations/etc. must be implemented. Such mechanisms are key to ensure that both institutions and individuals understand they have a meaningful role to play and to ensure the good implementation of long-term strategies.

7. COASTAL AND OCEAN MANAGEMENT – Promote and strengthen multi-scale (within countries), multi-state (transboundary) and multi-sectoral policy tools and legislation for coastal and ocean management. This prevents further degradation of coastal and ocean ecosystems, enables the restoration of critical systems, and develop/strengthen coastal societies' adaptive capacity.

WHY: To enable sustainable economic growth and avoid social breakdown of countries using the services from a healthy ocean (e.g. Blue Growth, Integrated Coastal Zone Management, Marine Spatial Planning, Ecosystem Based Adaptation). This point emphasizes that cooperation can be beneficial at various levels, and also that some tools already exist to implement transboundary action.

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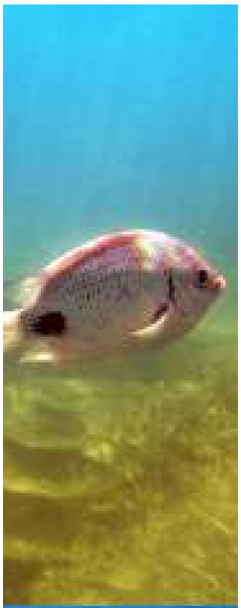
"Bridging the Gap between Ocean Acidification and Economic Valuation"

Oceanographic Museum, Principality of Monaco.
12-14 January 2015

The Third International Workshop on the Socio-Economic Impacts of Ocean acidification gathered 53 experts from the natural and social sciences from 20 countries. The workshop considered how ocean acidification could affect different marine resources and coastal communities, and identified potential solutions. Despite uncertainties, particularly related to combined effects with other major environmental stressors, we know enough to act, and action should be taken now. Here is a synthesis of key messages on the main outcomes from the workshop dicussion:

Key messages:

- **Communities and activities most at risk include:**
  - **Small scale fisheries and mariculture in developing countries;**
  - **Poorer communities and social groups dependent on subsistence fisheries, with potential gender inequalities;**
  - **Economies reliant on aquaculture or threatened ecosystems, such as coral reefs;**
  - **Poorly diversified local economies.**
- **Economic impacts of ocean acidification on tourism may include loss of profits and employment, as well as loss of tourist infrastructure due to decreased storm protection from reefs.**
- **Reducing the root cause of ocean acidification – CO_2 emissions – must remain the primary goal, even if adaptation options can be considered to buy time.**
- **Adaptation methods include behavioral change, infrastructure investment and building economic resilience through loans, tax credits, taxes, insurance, prizes and risk pooling.**
- **Governance reforms should include mitigation and adaptation actions at national and sub-national, as well as multilateral collaboration, capacity building and technology transfer.**
- **Build capacity and awareness of ocean acidification at influencer-level and to include it in national education agendas.**
- **There are significant gaps in our ability to characterize and model the local/regional ocean acidification processes and their impacts on the food supplies and ecosystem.**
- **Open-ocean models on ocean acidification are not applicable to coastal assessment and there are currently very few socio-economic models at a relevant scale for use by coastal communities and managers.**
- **Ocean acidification impacts need to be assessed in relation to existing trends, e.g. declining labour and incomes in capture fisheries, growth of aquaculture, and the impacts of other environmental stressors.**



What can communities do?

Research needs

Information for decision-making

- Improve awareness and knowledge at all levels, including on ocean acidification science, on the costs and effectiveness of adaptation and mitigation actions, and disseminate knowledge of lessons learnt and best practices.
- Support and extend research initiatives on ocean acidification and linked stressors, including monitoring, particularly for vulnerable coastal communities.
- Develop transdisciplinary food-web models for species of interest (capture and cultural) that begin to address the complexities of the coastal system and the potential impact on human well-being.
- Develop good practice two-way communication between scientists and end users.

Local and national management

Adaptive management to address complexity

- Improve coastal ecosystem resilience through effective fisheries and aquaculture management, restoration of fish stocks and biodiversity.
- Build community resilience by supporting diversified coastal community economies and increasing community engagement in co-management, e.g. fisheries.
- Explore innovative financing for adaptation (tourist taxes, user fees, public-private partnerships).
- Build ecosystem resilience by reducing local stress factors and creating marine protected areas.
- Broaden opportunities for coastal communities by developing tourism attractions based on healthy reef systems and potential alternative leisure activities.

International policy

Dynamic leadership to facilitate change

- Work to achieve urgent reduction in CO_2 emissions. We have very little time to reach substantial cuts in emissions and avoid tipping into dangerous zones.
- Place ocean acidification, along with other climate change drivers, as a high priority for more countries.
- Mainstream ocean acidification into global, regional and national policies, plans and investment strategies for climate change, for oceans, and in fisheries and coastal management.
- Foster public and private investment in social, economic and environmental capital in communities and regions considered most vulnerable.
- Protect blue carbon sinks and design tools to include them in carbon trading.
- Make ocean acidification projects eligible to the Green Climate Fund.

The views expressed in this report are those of the workshop participants and do not necessarily reflect those of the Centre Scientifique de Monaco and the International Atomic Energy Agency.

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For list of participants and full report, please visit:
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