THE MONACO OCEAN ACIDIFICATION ACTION PLAN

Summarizing progress, setting out priorities

Heralding the next era of action on ocean acidification

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OCEAN ACIDIFICATION presents a very real threat to all those depending on the sea and its resources around the world in the coming decades. My interest in this issue goes back many years. In 2008 I hosted the Second International Symposium on The Ocean in a High-CO_2 World in Monaco. That meeting was part of a process that continues today to transform awareness of ocean acidification and its inclusion as a key issue in global policy discussions. It has been a busy decade of bringing ocean chemistry and marine biology disciplines closer together, as well as forging new and vital links with a wide range of individuals and organizations to alert them to this component of human-driven global change, and to invite them to urgently help spread knowledge and awareness within their communities.

As I reflect on the past decade, and look towards the next one, I realize the need to continue to build our scientific knowledge, to ensure climate policy fully embraces the need to act on ocean acidification, as well as the need to redouble our efforts to 'get ahead' of the acidification curve. I also now realize we need to consider ocean acidification knowledge alongside other major ocean stressors such as warming, over-fishing and deoxygenation. The time to act is running out. With these new challenges in mind I am delighted to see this Action Plan developed through work supported by my Foundation. I renew my call for working together closer to tackle what is now one of the most significant ocean challenges of our generation.

HSH Prince Albert II of Monaco

JUST OVER A DECADE AGO the world first recognized the problems that some coastal communities and economic sectors were starting to experience from progressive ocean acidification. The chemical process behind ocean acidification was described in the 1950s, but it wasn't until the 1980s that observations from the north-east Pacific Ocean showed that real changes were already happening. By the 1990s coral reef biologists began to explore this issue and the First Symposium on The Ocean in a High CO_2 World, held in 2004, provided the opportunity for the global science community to start exploring how ocean acidification might affect the ability of marine organisms to produce their shells and skeletons from calcium carbonate minerals. We now know that ocean acidification is adding to other significant global drivers of marine ecosystem change, such as ocean warming and deoxygenation.

Since 2004, much progress has been made in investigating, understanding, evaluating and communicating the challenges caused by ocean acidification. Those advances have not only transformed our understanding of the problem, and increased our concern of the severe and urgent threats now faced, but have also resulted in new organizational frameworks to support scientific research and international policy discussions.

> ***"Ocean acidification – it is the silent storm. It can't be heard, it can't be felt, it can't be seen, but scientists are measuring it."***
>
> CAROL TURLEY, PLYMOUTH MARINE LABORATORY, UK

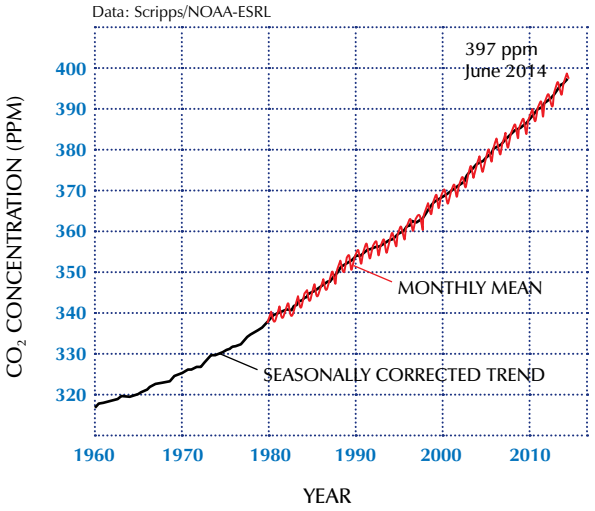
This Action Plan was developed by the Ocean Acidification international Reference User Group (OAiRUG), with representatives from both the scientific and research users communities. The Plan aims to share progress and set priorities for developments in science and policy to keep pace with impacts we are starting to see in ecosystems and economic sectors most vulnerable to ocean acidification. This plan is as much for governments, policy advisers and decision makers, as it is for new stakeholders and the existing ocean acidification experts who form the current 'ocean acidification community'. Whilst this plan is not comprehensive, it highlights major achievements and is intended to take stock of scientific and political activities, whilst also fostering a broader debate on priorities for action in the coming decade.

Ten Monaco Action Plan priorities to address ocean acidification

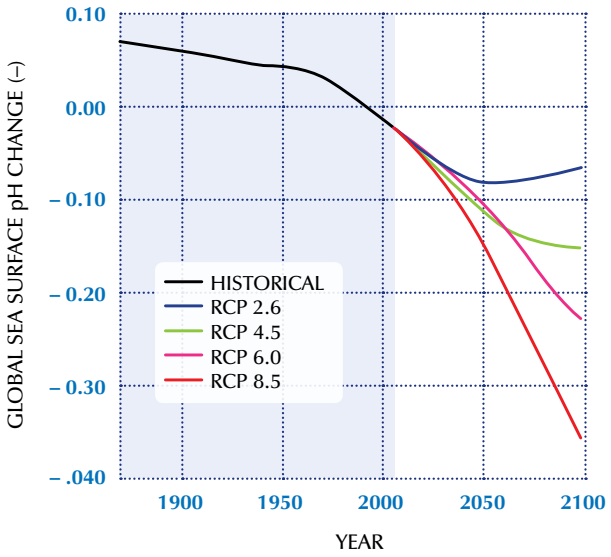
1. Shift the emphasis of scientific research from individual species to ecosystems, in order to understand impacts on food webs and to assist the parameterization of models.
2. Devise long-term experimental studies to understand adaptation as well as acclimation.
3. Consider multiple factors, underlying principles, and natural variability to gain better confidence of future impacts under 'real world' conditions.
4. Support efforts to reduce anthropogenic CO_2 emissions at sufficient scale and speed to avoid dangerous climate change and dangerous ocean acidification.
5. Invest in prudent adaptive marine management approaches to best manage carbon sinks, to foster greater ecosystem resilience, and protect genetic diversity.
6. Match the development of ocean acidification observational networks to the needs of communities, industries, regions and governments in order to secure the scale of investment and support needed to develop forecasting capabilities.
7. Sustain international collaborative coordination efforts that support national research programmes, maintain standards, data and common systems, support effective deployment and interpretation of monitoring efforts, and enhance communication with end user communities.
8. Identify and develop relationships with new stakeholders that are likely to be affected by ocean acidification.
9. Support research to map the current and projected economic impacts of ocean acidification.
10. Invest in education and communication, aimed at a wide public audience, and scientific training to support capacity development in vulnerable regions that currently lack such capabilities.

Where are we with the science on ocean acidification?

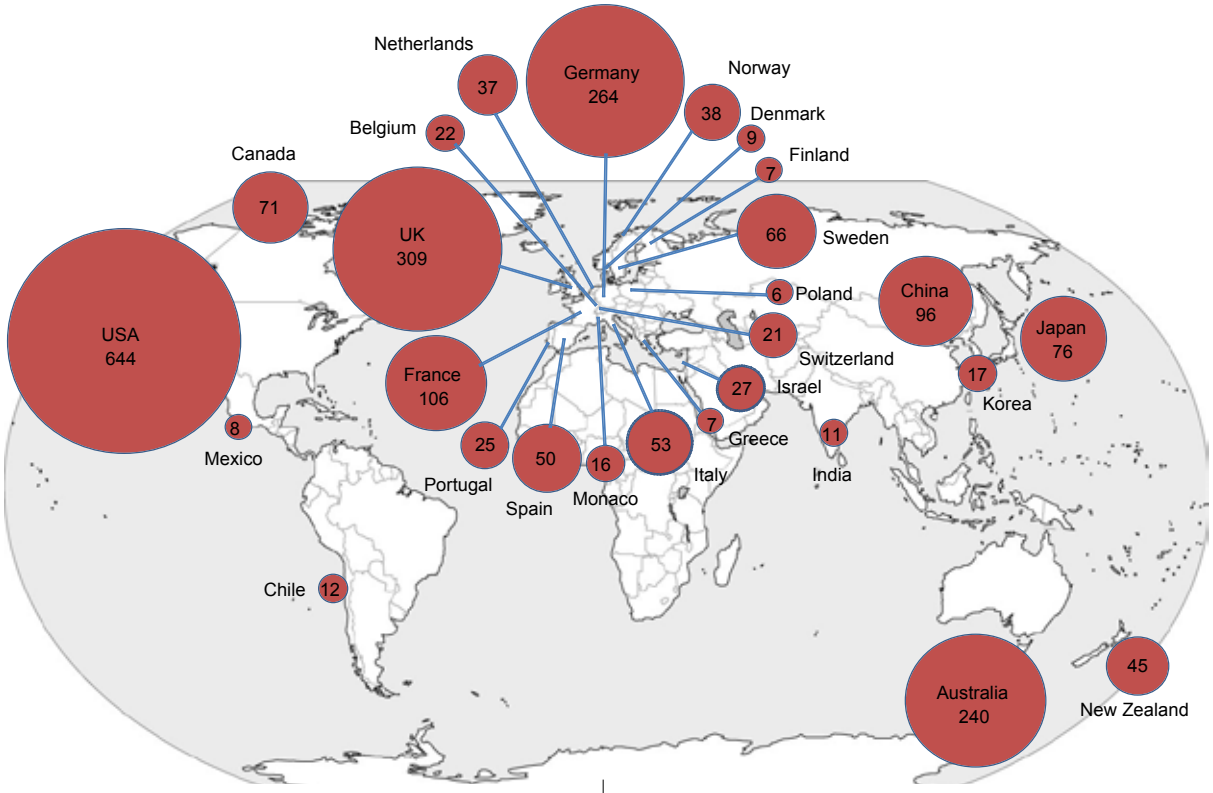
THE ROOT CAUSE of ocean acidification is the rising concentration of the carbon dioxide (CO_2) in the atmosphere.



The severity of future ocean acidification depends on the scale of future CO_2 emissions, shown here for the four IPCC pathways: RCP 2.6, lowest emissions (atmospheric CO_2 at ~421ppm in 2100); RCP 6.0, low emissions (~538ppm); moderate emissions (~670ppm); and RCP 8.5, high emissions (~936ppm). After Bopp *et al.* 2013.



National involvement in ocean acidification research, based on first authors' addresses for peer-reviewed papers published in 2005–2014 for countries with 5 or more ocean acidification publications.
(P. Williamson. Data from the International Atomic Energy Agency (IAEA) Ocean Acidification International Coordination Centre)



Following the dramatic increase of interest in ocean acidification around 10 years ago, several countries launched national research programmes. These have examined the problem using a wide range of approaches – laboratory experiments, sediment records, field observations around natural ocean volcanic seabed seeps of CO_2 and upwelling areas, experiments bringing a small part of the natural environment under controlled conditions where CO_2 concentrations can be artificially manipulated, and free ocean CO_2 enrichment experiments.

This work has already demonstrated with high confidence that ocean acidification:

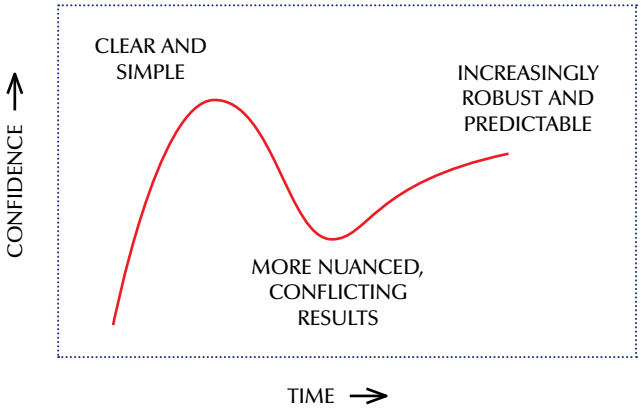
- is caused by CO_2 emissions,
- is changing the carbon chemistry of the ocean,
- is happening now, and
- is happening very rapidly.

We know that ocean acidification is occurring in association with other ocean stressors and that this cocktail of effects has the potential to severely impact ecosystem services in the ocean.

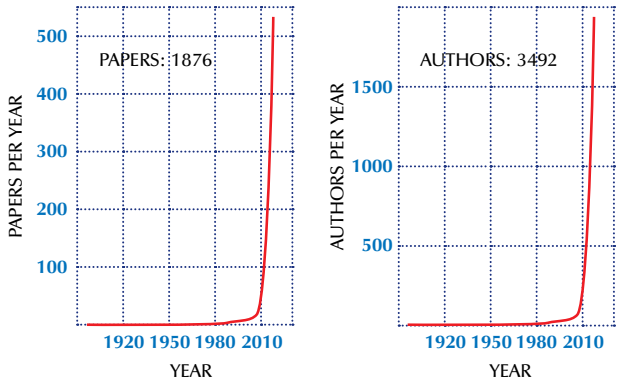
Taking all factors together, anthropogenic driven acidification of the ocean over the past 250 years represents the largest such event in at least 55 million years of the Earth's history, and almost certainly the fastest such changes in at least the past 300 million years.

An era of nuance: a paradox and a challenge

After S. Doney



OA young field of research



	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013
PAPERS	24	24	36	71	128	166	217	314	357	539
AUTHORS	58	92	120	221	341	554	640	1068	1312	1868

After Gattuso and Hansson 2011 and Gattuso *et al*. 2011.

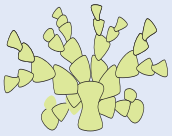
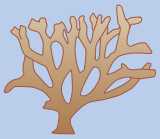
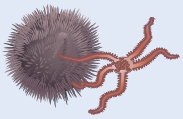
The science around ocean acidification is growing rapidly and results from recent research are changing our initial perceptions of the nature of possible impacts on ocean ecosystems. Most of the earliest experiments were 'short and simple' and showed considerable variability in results. Subsequently there has been greater appreciation of the importance of experimental length, physiological condition and interactions with other factors – providing better understanding and hence improving our forecasting skill for 'real world' conditions. The increase in ocean acidification publications (and the number of researchers involved) has been particularly dramatic since 2008, following the Second International Symposium on The Ocean in a High CO_2 World.

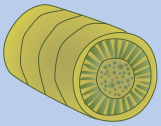
We now know that very many species of ecological, commercial and cultural importance are likely to be adversely impacted by ocean acidification. However, the response varies greatly between species, and some may be positively affected; furthermore, responses can vary over time through acclimation and multi-generational adaptation. Thus there remains considerable uncertainty regarding the overall impact at the ecosystem scale. Combining the results from the very many laboratory experiments (meta-analyses) shows that significant negative effects include reduced survival, impaired calcification, slowed growth and development, and decreased abundance. Positive effects (arising from enhanced photosynthesis) include increased growth rates in some fleshy algae and diatoms. Such positive effects must be seen in the context of the far broader array of negative responses that will inevitably interact and result in a very changed ocean environment in the future – unless there are rapid and substantive reductions in CO_2 emissions.

Analyses of multiple data sets, expert surveys, and assessments have been used by the international scientific community to determine the confidence level surrounding the science of ocean acidification. For example, the 2013 Summary for Policymakers published by the International Geosphere – Biosphere Programme (IGBP), the Scientific Committee on Oceanic Research (SCOR) and the Intergovernmental Oceanographic Commission of UNESCO (IOC-UNESCO). That report reviewed the state of scientific knowledge on ocean acidification, based on research presented at the Third International Symposium on The Ocean in a High CO_2 World, held in Monterey, California, in September 2012, the largest gathering of ocean acidification experts to date. Similar conclusions were reached in subsequent assessments of ocean acidification impacts by the Convention on Biological Diversity and the Intergovernmental Panel on Climate Change.

Research by the Mediterranean Sea Acidification in a Changing Climate project (MedSeA) has documented how ocean acidification impacts are being felt at a regional sea-scale. Their ten facts on ocean acidification and warming come from the combined findings of more than 100 scientists from 22 institutions in 12 countries and include the information that the Mediterranean Sea has already warmed nearly 1°C over the last 25 years, with increases in acidity of around 10% over that period (http://medsea-project.eu/wp-content/uploads/2011/08/10_facts_english.pdf).

Summary of effects of acidification among selected taxonomic groups. Effects are either a mean percent increase or decrease in a given response, or as no overall positive or negative response. After Kroeker *et al.* 2013.

TAXA	RESPONSE	MEAN EFFECT
 Calcifying algae	Survival	
	Calcification	
	Growth	
	Photosynthesis	–28%
	Abundance	–80%
 Corals	Survival	
	Calcification	–32%
	Growth	
	Development	
	Abundance	–47%
Coccolithophores	Survival	
	Calcification	–23%
	Growth	
	Photosynthesis	
	Abundance	
Molluscs	Survival	–34%
	Calcification	–40%
	Growth	–17%
	Development	–25%
	Abundance	
 Echinoderms	Survival	
	Calcification	
	Growth	–10%
	Development	–11%
	Abundance	

TAXA	RESPONSE	MEAN EFFECT
Crustaceans	Survival	
	Calcification	
	Growth	
	Development	
	Abundance	
Fish	Survival	
	Calcification	
	Growth	
	Development	
	Abundance	
Fleshy algae	Survival	
	Calcification	
	Growth	+22%
	Photosynthesis	
	Abundance	
Seagrasses	Survival	
	Calcification	
	Growth	
	Photosynthesis	
	Abundance	
 Diatoms	Survival	
	Calcification	
	Growth	+17%
	Photosynthesis	+12%
	Abundance	

- Not tested or too few studies
- Enhanced <25%
- No overall +ve or -ve response
- Reduced <25%
- Reduced >25%

Differing levels of confidence on the science around ocean acidification

Derived from *Summary for Policy Makers* IGBP, IOC, SCOR 2013.

CONFIDENCE	SCIENCE
VERY HIGH	The capacity of the ocean to act as a carbon sink decreases as it acidifies
	Ocean acidification is caused by CO_2 emissions from human activity to the atmosphere that end up in the ocean
	The legacy of historical fossil fuel emissions on ocean acidification will be felt for centuries
	Anthropogenic ocean acidification is currently in progress and is measurable
	Reducing CO_2 emissions will slow the progress of ocean acidification
HIGH	The ocean is acidifying more rapidly than it has in millions of years
	Multiple stressors compound the effects of ocean acidification
	Cold-water coral communities are at risk and may become unsustainable
	Some seagrasses and phytoplankton species may benefit from ocean acidification
	The combination of ocean acidification and temperature negatively affects many organisms
	Molluscs (such as mussels, oysters and pteropods) are one of the groups most sensitive to ocean acidification
	If CO_2 emissions continue on the current trajectory, coral reef erosion is likely to outpace reef building sometime this century
	The varied responses of species to ocean acidification and other stressors are likely to lead to changes in marine ecosystems, but the extent of the impact is difficult to predict
MEDIUM	Anthropogenic ocean acidification will adversely affect many calcifying organisms
	Pteropod (marine snail) shells are already dissolving
	Ocean acidification may have some direct effects on fish physiology, behaviour and fitness
	Nitrogen fixation in some cyanobacteria may be stimulated by ocean acidification
	Declines in shellfisheries will lead to economic losses, but the extent of the losses is uncertain
	Negative socio-economic impacts of coral reef degradation are expected but the size of the costs is uncertain
LOW	Impacts of ocean acidification on ecosystems may affect top predators and fisheries
	Ocean acidification will alter biogeochemical cycles at a global scale

Lessons from the past

There have been periods in Earth's history where we have indications that the oceans have been acidified (a lower pH than today). For instance, at the end of the Permian, ca. 251 Myr ago or at the Paleocene-Eocene Thermal Maximum (PETM), 55 Myr ago. These acidification events were also triggered by a carbon perturbation but had a different origin (volcanism and methane clathrates, respectively) than today. Nevertheless, all are characterized by catastrophic extinctions and biodiversity loss.

In brief:

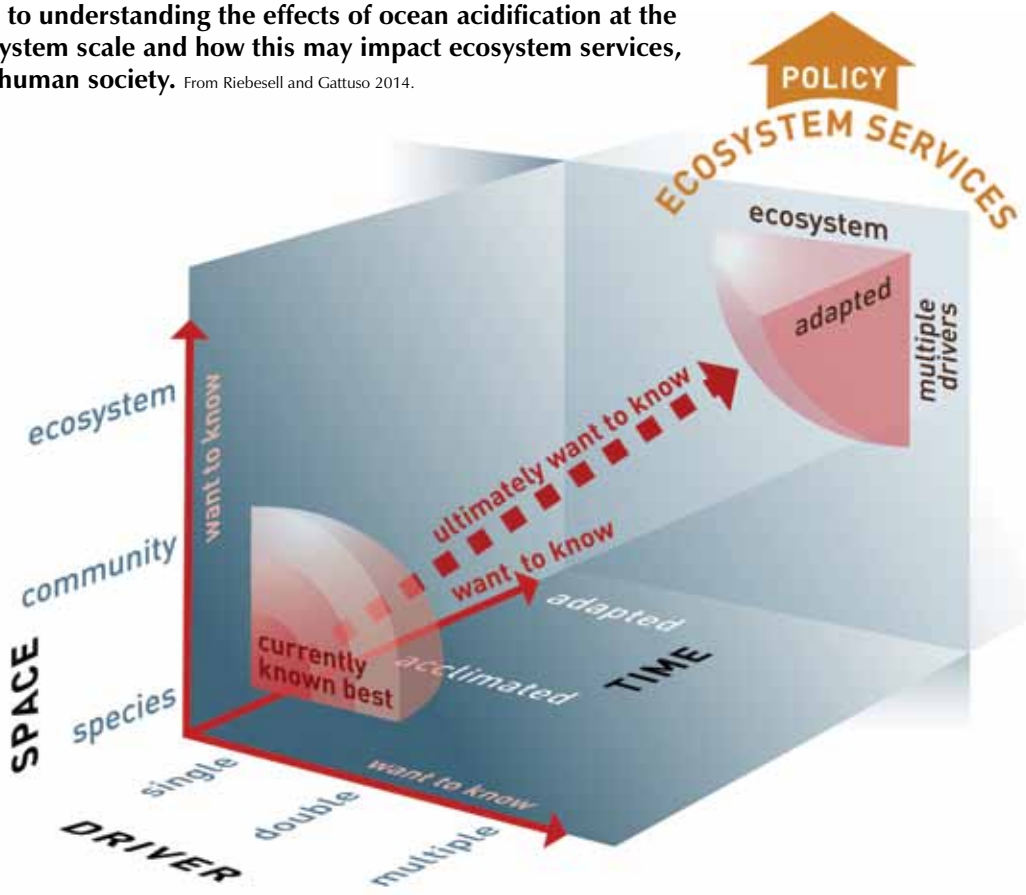
- Ocean acidification has occurred in Earth History.
- Ocean acidification is just one of the symptoms of a carbon perturbation. It goes hand-in-hand with global warming, climate change and deoxygenation of the deep ocean.
- It is a common misconception that high atmospheric pCO_2, per se, goes hand-in-hand with reduced biocalcification.
- Depending on the rate of the carbon perturbation, only pH decreases, or pH and saturation state decline in concert.
- The rate of the anthropogenic carbon perturbation is, to our best knowledge, at least 10 X faster than anytime during the last 300 million years.
- There is no perfect analogue for today's disruption of the carbon cycle.
- The geological record suggests that the current acidification is potentially unparalleled in at least the last 300 million years of Earth's history, and raises the possibility that we are entering unknown territory of marine ecosystem change.

Understanding the risks and consequences of ocean acidification and recognizing that both ocean acidification and global warming are caused by anthropogenic CO_2 emissions will hopefully help to set in motion a stringent climate policy worldwide. The only solution to neutralize ocean acidification and global warming is a long-term mitigation strategy to limit future release of CO_2 to the atmosphere and/or enhance removal of excess CO_2 from the atmosphere.

Knowledge gaps

Past research has enabled a high confidence for the effects on ocean chemistry; however, confidence in the many potential biogeochemical and biological impacts (including the effects on physiology, behaviour and genetics) is far lower. There are major gaps in knowledge on the combined effects of ocean acidification with other stressors, whole ecosystem responses, implications for top predators and the socio-economic consequences of such changes for different human communities. These are all clearly urgent priorities for research over the coming years.

The scientific challenge of moving from the current knowledge base to understanding the effects of ocean acidification at the ecosystem scale and how this may impact ecosystem services, and human society. From Riebesell and Gattuso 2014.



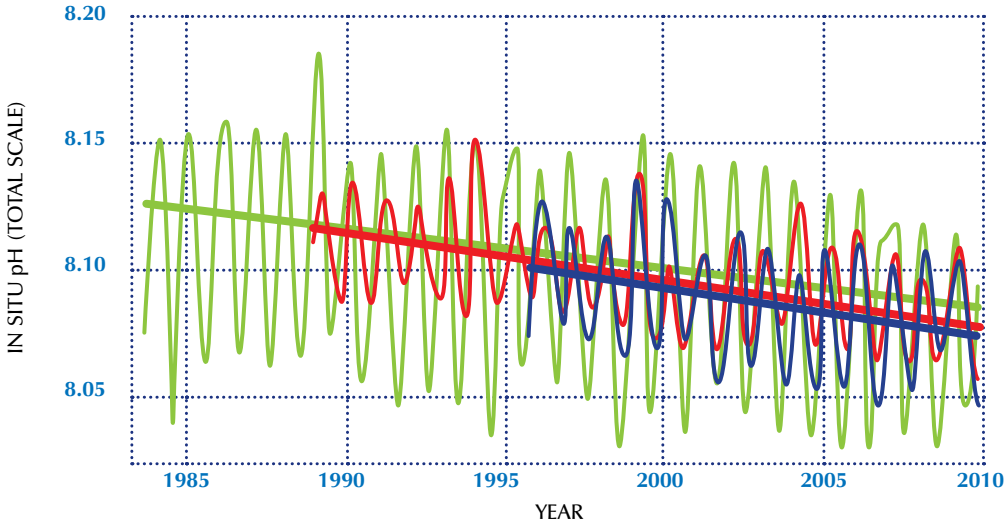
Keeping track of ocean acidification – the importance of coordinated research and ocean observations

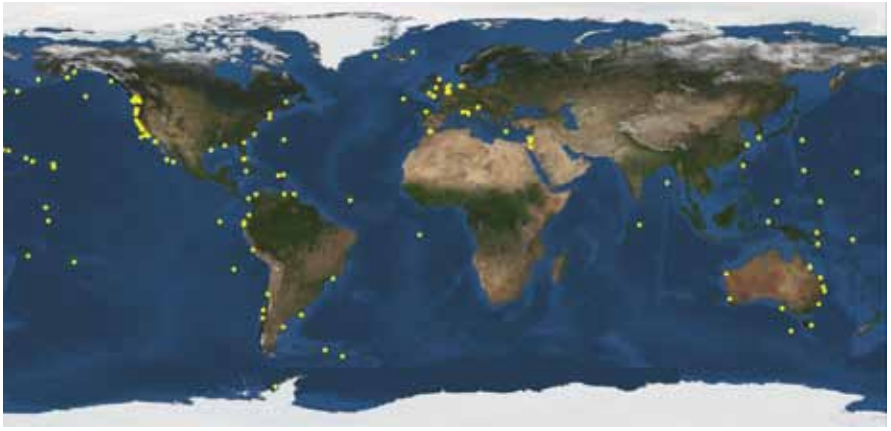
DIRECT OBSERVATIONS from the last 25 years and reconstructions (from coral composition) going back to the 1940s show a trend of increasing dissolved CO_2 in the upper ocean, whilst pH is falling. These trends closely match the observed changes in atmospheric CO_2 concentrations.

Whilst it is important to maintain these long-term records, providing firm evidence of a global trend towards more acidic conditions in the ocean, a wider need has developed for fit-for-purpose, regionally-based but globally-integrated ocean acidification observations – to complement other chemical and biological monitoring, and to contribute to relevant research, by increasing our understanding of the processes involved. Thus it is not sufficient just to measure pH or other components of the carbonate chemistry system, since the rate and severity of ocean acidification depends not only on other physico-chemical conditions (including temperature, freshwater inputs, upwelling and nutrients) but also biological influences (primary production, decomposition).

The Global Ocean Acidification Observing Network (GOA-ON www.goa-on.org) was established in 2013 as a collaborative, international approach to address the need for a much broader suite of observations. In particular, GOA-ON aims to document the status and progress of ocean acidification in open ocean, coastal, and estuarine environments; to improve our understanding of the drivers and impacts of ocean acidification on marine ecosystems; and to provide the spatially – and temporally – resolved data necessary to optimize the modelling of ocean acidification and its impacts.

Long-term trends of surface seawater pH, showing Bermuda Atlantic Time-series Study (BATS, 31°40'N, 64°10'W; GREEN) and Hydrostation S (32°10', 64°30'W) from 1983 to present; Hawaii Ocean Time-series (HOT) at Station ALOHA (A Long-term Oligotrophic Habitat Assessment; 22°45'N, 158°00'W; RED) from 1988 to present; and (c) European Station for Time series in the Ocean (ESTOC, 29°10'N, 15°30'W; BLUE) from 1994 to present. After Rhein *et al.* 2013.



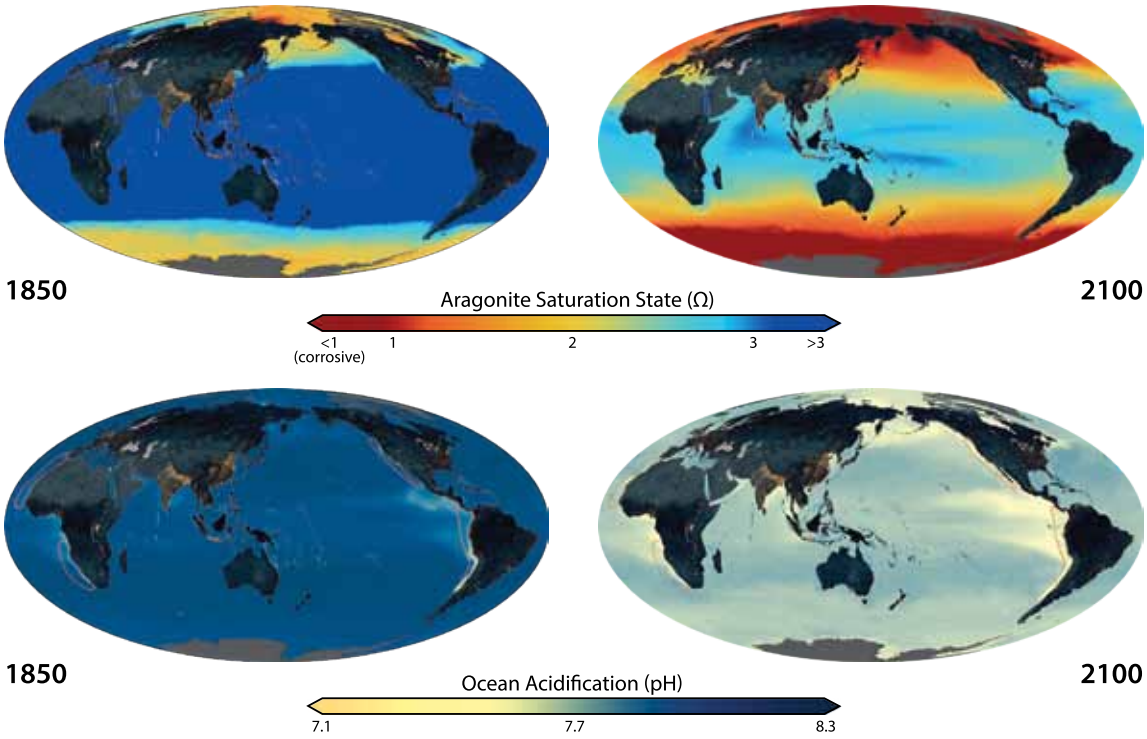


Current ocean carbon observing network including time-series stations and moorings.
After GOA-ON www.goa-on.org

The importance of obtaining widespread measurements on ocean acidification has been endorsed by the UN General Assembly[1], the Convention on Biological Diversity, and by many governmental and non-governmental bodies who have recently assisted the scientific community in developing GOA-ON. A further boost to such efforts was given at the first 'Our Ocean' conference hosted by John Kerry at the U.S. Department of State in Washington, D.C. in June 2014. The Action Plan arising from the conference included the need to 'create a worldwide capability to monitor ocean acidification'.

1. Paragraph 153 of 68/70, passed 9 December 2013: "...encouraged States and competent international organisations and other relevant institutions, individually and in cooperation, to urgently pursue further research on ocean acidification, especially programmes of observation and measurement..."

Top: Aragonite saturation; Bottom: Surface ocean pH, in 1850 and 2100 using high CO_2 emissions scenario (RCP 8.5). Model projections calculated by MPI-ESM-LR, data provided by Tatiana Ilyina from Max Planck Institute for Meteorology. Design by Globaia. Adapted from IGBP, SCOR, IOC 2013.



GOA-ON builds on the existing data gathering network for ocean carbon observing using repeat hydrographic surveys, time-series stations, floats, gliders and volunteer observing ships, and aims to provide the best information available on the current inventory of global OA observing platforms.

The further development of GOA-ON will be closely aligned to the Framework for Ocean Observation of the Global Ocean Observing System (GOOS) and the International Ocean Carbon Coordination Project (IOCCP), while also working closely with the Intergovernmental Oceanographic Commission (IOC of UNESCO), the Ocean Acidification International Coordination Centre (OA-ICC of IAEA), and other relevant bodies.

The future goals of GOA-ON include facilitating additional measurements in geographic areas of high concern, together with associated capacity-building; strengthening of linkages with experimental and theoretical studies; maintaining and extending communications with the ocean observing community; establishing effective and quality-controlled international data management and data sharing through distributed data centres; and encouraging the development of synthesis products based on GOA-ON measurements. However, all the necessary level of support and resources to achieve all these goals has yet to be secured.

An overall goal for the next decade is to use the observing network as the basis for ocean acidification forecasting systems (both short-term and long-term) with focus on vulnerable areas of the ocean. This process should invigorate the observing network to focus on stakeholder needs and to incentivize and professionalize the services that can then be offered to a wide range of stakeholders.

WENDY SCHMIDT OCEAN HEALTH XPRIZE

The XPRIZE gearing up to measure ocean acidification: incentivizing action

XPRIZE is a non-profit organization that encourages technological development for societal benefit, through incentivized competition. In spring 2012 the XPRIZE turned its attention to the ocean announcing the Wendy Schmidt Ocean Health XPRIZE: a $US2 million global competition to challenge teams of engineers, scientists and innovators to create pH sensor technology that will affordably, accurately and efficiently measure ocean chemistry.

Most current pH sensor technologies are too costly, imprecise, or unstable to allow for the collection of sufficient reliable knowledge on the state of ocean acidification. Two $US1 million prizes are being offered – one for accuracy and another for affordability.

Looking to the future, a key issue will not just be awarding the prizes to the winning teams but investing in 'post-prize market readiness'. This is with the view to ensuring that within the context of the needs and priorities of a global observation network for ocean acidification, the competition-winning sensors can be rapidly deployed around the world and in a way that has maximum impact on increasing in-water observation of acidification, set in the context of future ocean acidification forecasting priorities.

The need to act on ocean acidification – rising costs and closing doors

A CONSISTENT THEME over the last decade of research is that some changes expected for the distant future are happening faster than originally estimated. The changes are progressive, so in the coming decades more coastal communities, particularly in vulnerable areas, e.g. places with upwelling areas and in higher latitudes, may be affected by loss of productivity and related incomes. The reality is that the more CO_2 emitted to the atmosphere, the greater the acidification that will occur across the ocean.

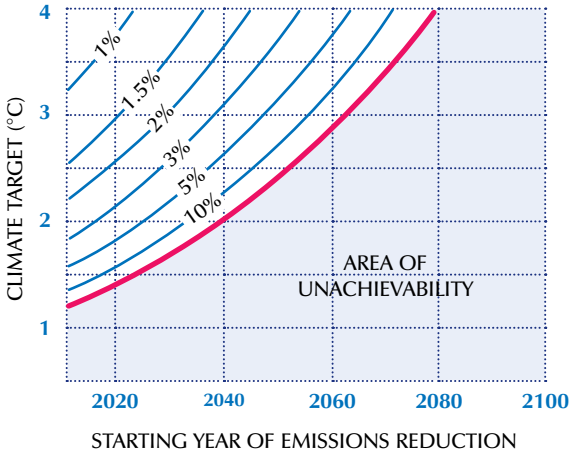
Shellfish losses in Oregon and Washington: a window on the future?

Some of the globally-projected impacts of ocean acidification for 2100 have already started to materialize at the local level. In 2007, shellfish hatcheries in Oregon and Washington experienced an unprecedented 70-80% mortality of oyster larvae, threatening an industry that generates about $US270 million annually for the coastal economy.

Hatchery operators teamed up with scientists and determined that upwelled, acidified waters were contributing to the larval mortalities. Independently, scientists reported in 2008 that upwelling of acidified sea water onto the continental shelf of North America was corrosive to the shells and skeletons of corals, plankton, and shellfish. Whilst the upwelled water has always had lower pH than surface waters elsewhere, such effects are now being enhanced by the higher concentrations of atmospheric CO_2, increasing the frequency and severity of times when corrosive conditions exist.

Through state and federal funding, shellfish growers now have monitoring equipment at their growing sites, allowing for adaptation processes to be implemented as required. The detection of ocean acidification-mediated impacts in the U.S. Pacific Northwest reflects in part the capacity of U.S. scientific community and industry to detect and adapt to the phenomenon: a capacity that is largely absent from ocean acidification hotspots in the developing world.

Required emissions reduction rates (% per year) as a function of the starting date of the Global Mitigation Scheme and the desired climate target (red line). After Stocker 2013.



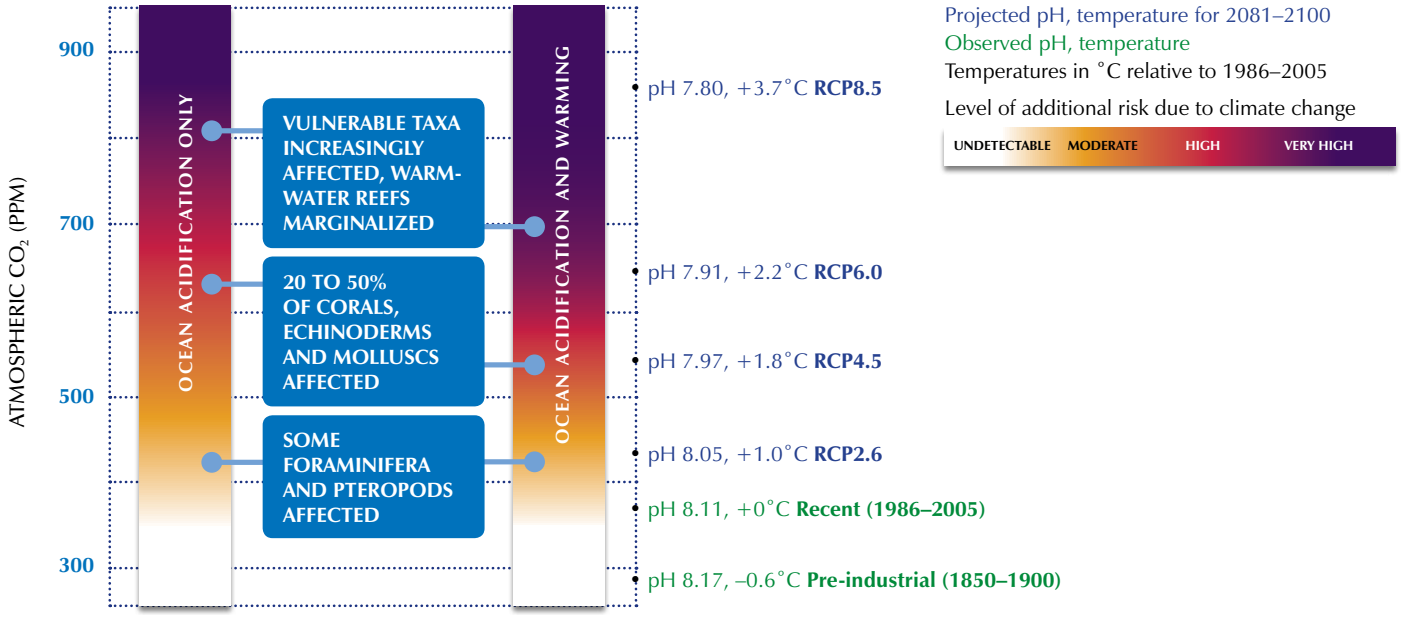
Reducing fossil fuels emissions, cement manufacturing and deforestation are the only realistic ways to achieve the required reduction in atmospheric CO_2. Achieving significant reductions is a major challenge, but sustained long-term action can be made at lower costs compared to the costs of inaction. In the example of the Pacific north-west, the challenges in operating hatcheries under current seawater conditions are already such that one farm has now relocated to Hawaii to circumvent the situation.

Achieving stabilization of atmospheric CO_2 concentrations between 500 and 550ppm CO_2 are estimated to cost around 1% of the annual global GDP (Stern, 2007). The longer the delays are in making cuts in emissions the greater the scale and severity of the cuts that will be needed and by association the total global financial burden.

The UN Framework Convention on Climate Change (UNFCCC) is the pre-eminent global mechanism through which action could be taken on ocean acidification.

The risks to marine organisms impacted by ocean acidification (OA) or warming extremes combined with OA.

After IPCC AR5. Full Synthesis Report 2014, Fig 2.5.



Oceans retreat leaders call on international mitigation efforts and the revision of the UNFCCC 2°C climate target to fully embrace ocean impacts such as rising sea levels and acidification effects

A high level retreat on *Sea Change: Developing Strategies for Rising Sea Levels and Ocean Acidification* was held at Sunnylands, from the 10–12 October 2014. Hosted by The Annenberg Foundation Trust at Sunnylands, HSH Prince Albert II of Monaco, His Excellency Anote Tong, President of the Republic of Kiribati, and Scripps Institution of Oceanography, the retreat outcome included the comments:

"Many participants agreed with the latest IPCC conclusions that limiting global warming to 2°C relative to pre-industrial levels would require further substantial reductions in greenhouse gas emissions beyond 2020. Participants also recognized the need to ensure that ocean impacts such as rising sea levels and acidification are fully factored into the international mitigation efforts and climate (or temperature) target review."

Addressing ocean acidification falls within the interpretation of Article 2 of the Convention, which focuses on stabilization of greenhouse gas (GHG) concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system.

The challenge is therefore moving from a predominant focus by world governments on reducing the GHG emissions to limit mean global warming to 2°C, to a focus on threshold atmospheric CO_2 levels – to avoid not only 'dangerous' climate change but also 'dangerous' ocean acidification. 'One size won't fit all' to address climate change and ocean acidification. Multiple indicators and targets are needed to address not just warming but also acidification, underlining the need for even deeper cuts in emissions. If the UNFCCC were to directly address ocean acidification in this way, it would be one of the key reasons for lower allowable emissions within the time frame of the 21st century.

Adaptation: Ocean acidification is a global issue relevant to human society but many countries do not yet have the capacity to study and understand this problem. A future agenda will need to include the resources for training and building adequate local capacity and expanding knowledge, so that ocean chemistry can be observed globally, early warning of change can be implemented, and to have some time to build adaptive capacity. The subsequent options for adaptation are nevertheless extremely limited and so the need to act immediately and significantly to reduce anthropogenic emissions remains the top priority. The CBD, for example, developed guidance for practical responses to the impacts of ocean acidification on marine and coastal biodiversity.

Mitigation: Mitigation is the only way to reduce the pace and extent of ocean acidification. It is not reversible on the timescale of human generations. Further and urgent international collaborative action is required for mitigation, but funds are currently limited. To support the UNFCCC process stakeholders and experts should define additional relevant climate targets to replace the traditional temperature target. Targeted collaboration between the UN, governments, states, NGOs, foundations, industry, financial markets, citizens and scientists to reduce and adapt to ocean acidification is key.

Enhanced international cooperation to address ocean acidification – supporting regional capacity and national programme activities

"We call for support to initiatives that address ocean acidification and the impacts of climate change on marine and coastal ecosystems and resources. In this regard, we reiterate the need to work collectively to prevent further ocean acidification, as well as enhance the resilience of marine ecosystems and of the communities whose livelihoods depend on them, and to support marine scientific research, monitoring and observation of ocean acidification and particularly vulnerable ecosystems, including through enhanced international cooperation in this regard."

RIO+20 OUTCOME DOCUMENT, PARAGRAPH 166, JUNE 2012

The SCOR, IGBP, IOC Symposium on The Ocean in a High-CO_2 World in Monterey, California in 2012 represents the largest gathering to date of researchers studying ocean acidification.

THE FIRST national project was the UK's Implications of CO_2 for the Marine Environment (IMCO$_2$ 2004–2008) whilst the European Project on Ocean Acidification in 2008 http://www.epoca-project.eu/ became the first international project dedicated to ocean acidification. In the four years between 2008 and 2012 eight nations instigated national research projects including regional sea-focused efforts such as the MedSeA project (medsea-project.eu; commenced in 2011 involving 12 countries). By 2012 national research efforts had spread to the UK, Germany, USA, Korea and Australia. The same period saw a significant ramping-up of policy effort and the introduction of specific legislation such as The US Federal Ocean Acidification Research and Monitoring Act in 2009.

Effort was directed at involving, informing, and receiving advice from stakeholders – the 'reference user group' concept. This was implemented at increasingly larger geographical scales. First applied to ocean acidification in the UK in 2004, this approach was then used to

The OAiRUG – and the RUG process it embodies – has the longest and most successful track record for any mechanism designed to connect end-users and decision makers to experts involved with ocean acidification research.

support national and regional research efforts in 2008 in Europe, before being broadened to new national research agendas in the UK, Germany, and the Mediterranean thus helping to more rapidly engage a broader stakeholder community in the challenges and issues to be faced from ocean acidification.

At the same time international symposia and meetings provided added coordination capabilities for the research community – most notably through the Ocean Acidification Working Group of the Surface Ocean Lower Atmosphere Study (SOLAS) and Integrated Marine Biogeochemistry and Ecosystem Research (IMBER) programmes and The Ocean in a High CO_2 World Symposia series.

Alongside these, wider efforts targeting international cooperation brought together natural and social scientists and economic experts to explore the societal impacts of ocean acidification and adaptation measures needed in order to detect how living ocean resources are harvested and used. The first international workshop on the socio-economics of ocean acidification, organized by the Centre Scientifique de Monaco (CSM) and the Environment Laboratories of the International Atomic Energy Agency (IAEA) in 2010, with support from the Prince Albert II of Monaco Foundation and the Government of Monaco, provided a venue for natural scientists and economists to introduce their perspectives on the topic of ocean acidification and to link these two communities. In 2012 the second international workshop gave particular attention to policy-related impacts of ocean acidification on livelihoods, trade and marine-based food supply. The workshop focused on fisheries and aquaculture, and regional aspects of species vulnerability and socio-economic adaptation. The workshop brought together 55 natural and economic scientists to provide policymakers with recommendations for regional priorities in fisheries and aquaculture. A third international workshop took place in early 2015 with a focus on ocean acidification impacts on coastal communities.

By 2011 it became apparent that the research challenge had changed from one of encouraging national research on ocean acidification, to one on how to support the new national research agendas that have successfully emerged from these efforts. In particular there was an increasing need to support international collaboration, offering greater efficiencies, capacity sharing, and reduced costs. Activities needed to set global standards for ocean acidification research are difficult if not impossible to fund nationally.

A new international project to fulfil this role was transposed into reality in 2013 in the shape of the Ocean Acidification International Coordination Centre (OA-ICC www.iaea.org/ocean-acidification), based at the Environment Laboratories of the International Atomic Energy Agency (IAEA) in Monaco. At the same time the existing, mostly European, reference user group for ocean acidification research was transitioned to a fully global initiative, with support from the Prince Albert II of Monaco Foundation. The Ocean Acidification international Reference User Group (OAiRUG http://www.iaea.org/ocean-acidification/page.php?page=2198) cooperates closely with the OA-ICC on communication activities. At a first meeting of the OAiRUG in 2013 HSH Prince Albert II announced the creation of a Monegasque Association on ocean acidification (Association Monégasque sur l'Acidification des Océans; AMAO; http://www.fpa2.com/article.php?idarticle=30&lang=en) to provide long-term coordination in Monaco and to further promote international activities on ocean acidification alongside existing efforts such as the OAiRUG and the Monaco-based OA-ICC.

Ocean Acidification International Coordination Centre

The OA-ICC was launched following recommendations by the SOLAS IMBER Ocean Acidification Working Group of IGBP and SCOR, and the EPOCA Ocean Acidification Reference User Group, and in response to the increasing concern of IAEA Member States. Isotopic and nuclear techniques are powerful tools to study the impact of ocean acidification on primary production, growth and calcification rates and the Environment Laboratories of the IAEA in Monaco have been studying ocean acidification since 2008.

It is supported by the IAEA 'Peaceful Uses Initiative' (PUI) through direct and in-kind contributions from several IAEA Member States and via research projects on ocean acidification, including national and programmatic contributions from: Australia, France, Italy (ENEA),

The Ocean Acidification international Reference User Group (OAiRUG)

The OAiRUG is an international forum for scientists and stakeholders on ocean acidification. It was formed in 2012 and first met in the autumn of 2013. Funded by the Prince Albert II of Monaco Foundation, its role is to work alongside the Association Monégasque sur l'Acidification des Oceans (AMAO) and the Ocean Acidification International Coordination Centre (OA-ICC) to bring scientists, policy advisers, decision makers, and end users together to:

- examine in detail the types of data, analyses and products that are most useful to managers, policy advisers, decision makers and politicians in explaining ocean acidification;
- take a major role in the process of ocean acidification science to policy knowledge transfer; and
- achieve wider society engagement and understanding of the implications of ocean acidification, in conjunction with other global environmental stressors such as ocean warming and deoxygenation.

http://www.iaea.org/ocean-acidification/page.php?page=2198

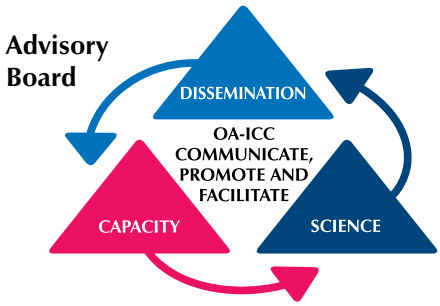
http://www.fpa2.com/article.php?idarticle=19

Japan, New Zealand, United Kingdom, United States of America, Integrated Marine Biogeochemistry and Ecosystem Research (IMBER), Surface Ocean Lower Atmosphere Study (SOLAS), Biological Impacts of Ocean Acidification (BIOACID), Mediterranean Sea Acidification in a Changing Climate (MedSeA), UK Ocean Acidification Programme (UKOA) and the NOAA Ocean Acidification Program (NOAA OAP).

Launched in summer 2012 the OA-ICC became fully operational in 2013 with an initial duration of 3 years. The project promotes overarching collaborative activities in three main areas:

- **Science –** Promoting activities to help advance ocean acidification research.
- **Capacity building –** Helping train tomorrow's experts on ocean acidification.
- **Communication –** Serving as a hub of information for different audiences.

The OA-ICC receives recommendations to its activities from an Advisory Board of experts in the field, other UN agencies and local partners.



In the last decade the ocean acidification research community has matured from individual scientists or small research groups undertaking specific projects, into a well-connected network of scientists. This international action has involved many people but is in no small part due to the work of the SOLAS IMBER Ocean Acidification Working group, the leadership of HSH Prince Albert II of Monaco and his Foundation and the Government of Monaco, the hosts and efforts of the three Symposia, and more lately the OA-ICC. However, if the research community is to continue to advance it is essential that interdisciplinary and transboundary coordination continues.

The integration of the efforts of the scientific community are beginning to bear fruit with the development of the GOA-ON.

Looking to the future the greatest challenges are sustaining the international coordination and outreach capacities and capabilities, and addressing the human dimension promoting the collaboration between the natural and social scientists. What is urgently needed is an up-to-date map of the current and projected economic impacts associated with ocean acidification so that mitigation measures can be put in place now and written into future plans.

Fundamental to the success of such ventures is an on-going programme of education and communication that reaches as wide an audience as possible. Alongside the continuing need to provide a range of communication tools such as posters, brochures and short films, priorities here might include:

- The development of a central web portal to provide visualization of observational data on progressive ocean acidification.
- The development of 'short course in a box' for schools providing materials about ocean acidification that can be used in the classroom and that could constitute a basis for developing school projects.
- For more advanced students the provision of training workshops and E-learning modules about ocean acidification. Especially focused on vulnerable regions like Latin America, Africa and South-east Asia such materials would significantly help build capacity, understanding and capabilities in areas currently lacking such abilities.

The Ocean in a High CO_2 World Symposium series

These symposia are a fundamental part of enhancing international collaboration to study ocean acidification and to raise its profile in the policy community. The progressively rising numbers of participants attending the Symposia is indicative of the growth of interest in this research topic.

The symposium series has been organized by the Scientific Committee on Oceanic Research (SCOR) in collaboration with the International Geosphere-Biosphere Programme (IGBP) and the Intergovernmental Oceanographic Commission (IOC) of UNESCO.

The Symposium series by numbers

First Symposium on The Ocean in a High CO_2 World – UNESCO Headquarters in Paris, France in May 2004; 125 researchers attended.

Second Symposium was held in Monaco in 2008; 227 researchers attended and the Monaco Declaration was formulated and subsequently launched by HSH Prince Albert II of Monaco. For the first time socio-economic and policy issues were included. http://www.iaea.org/newscenter/news/pdf/monacodecl061008.pdf

Third Symposium was held in Monterey in 2012. The four-day symposium brought together the world's leading experts in this rapidly expanding research field and 540 participants from 37 countries attended. Socio-economic research and policy issues featured prominently.

The Fourth Symposium will take place in Hobart, Australia in May 2016. http://www.highco2-iv.org

Further information at www.ocean-acidification.net – a portal on ocean acidification for policymakers, researchers and the public established by IGBP, SCOR, IOC-UNESCO, and OA-ICC. It contains the programmes and presentations of the above symposia.

The current nine focal areas for the Ocean Acidification International Coordination Centre (OA-ICC)

- Promoting the development of a global observing network on ocean acidification (GOA-ON).
- Supporting the provision of joint platforms and facilities for ocean acidification research as well as joint experiments.
- Promoting collaboration between natural and social sciences.
- Facilitating and promoting inter-comparison exercises.
- Encouraging the use of best practices in ocean acidification research.
- Providing access to a comprehensive on-line bibliographic database.
- Facilitating, coordinating and promoting data standards and sharing.
- Facilitating capacity building for students and scientists.
- Ensuring that high-quality information on ocean acidification is communicated to end users in an effective way (in close collaboration with OAiRUG).

OA-ICC Online Resources

Web site: http://www.iaea.org/ocean-acidification

News stream with daily posts on ocean acidification: http://news-oceanacidification-icc.org/

OA-ICC Bibliographic database with 2500 references: http://tinyurl.com/oaicc-data

OA-ICC Data Compilation on the biological response to ocean acidification: http://tinyurl.com/oaicc-biblio

Strengthening international policy action

> *"The give and take between the oceans and the atmosphere is integral to understanding the climate system and to stabilizing atmospheric carbon dioxide levels. Therefore, since the oceans act as a carbon sink and play an important role in the climate system, the impacts of CO_2 on the oceans must be considered within the mandate of the UNFCCC."*
>
> HARROULD-KOLIEB AND HERR, 2011

SINCE OCEAN ACIDIFICATION emerged onto the international arena in 2004 there has been increasing concern over what this may mean for the ocean, vulnerable coastal communities, and society more broadly in the future. National and international institutions published a number of scientific reports:

- An initial report by The Royal Society of London (2005) was rapidly followed by a range of publications from different fora including *The Future Oceans – Warming Up, Rising High, Turning Sour* (2006), the IAP statement on ocean acidification (2009), the UNEP *Environmental consequences of ocean acidification: a threat to food security Emerging Issues Bulletin* (2010), as well as a synthesis report *Impacts of ocean acidification on marine biodiversity* published by the Convention on Biological Diversity (2009).

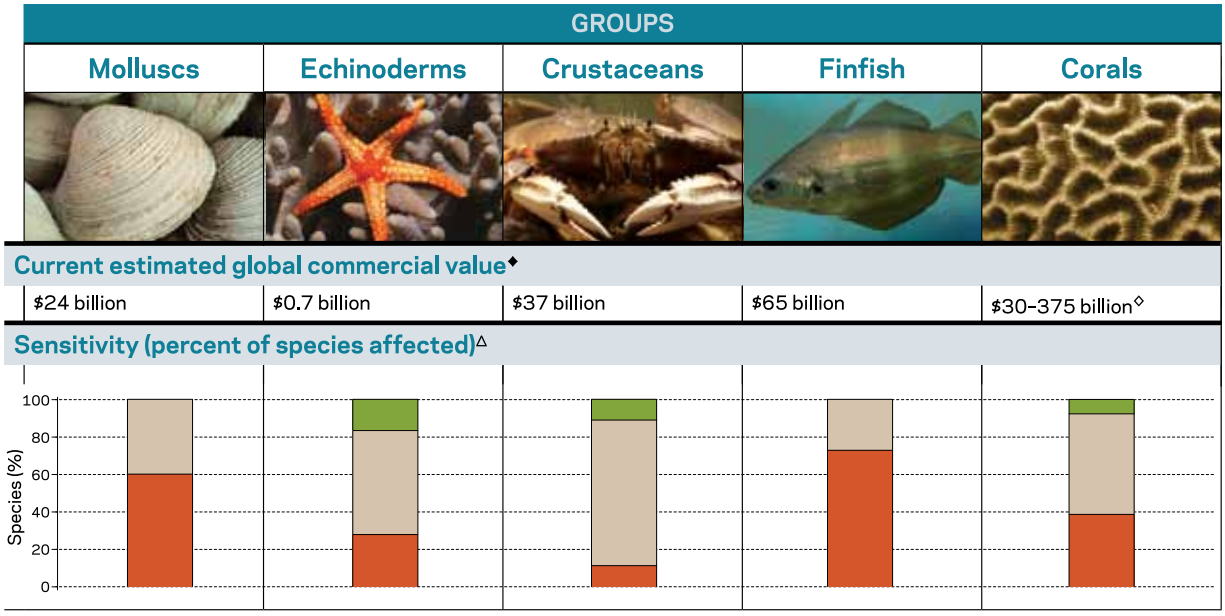
At the intergovernmental level, environmental and ocean related conventions, despite dealing with many different aspects of ocean governance and management since the 1970s, only started to integrate ocean acidification into their political agendas around 2005. Since then there has been a rapid increase in interest internationally, such as through the United Nations General Assembly as well as regionally, with, for example, OSPAR responsible for ocean management in the NE Atlantic. New scientific results coupled with an increased understanding of the economic worth of various marine organisms have triggered further concern and political attention. Especially since 2012 international fora have put increased emphasis on the need to enhance our knowledge about the impacts of ocean acidification.

At the 2012 Rio+20 conference, ocean acidification was a specific outcome (Number 166) in *The Future We Want*:

> *"We call for support for initiatives that address ocean acidification... and to support marine scientific research, monitoring and observation of ocean acidification and particularly vulnerable ecosystems, including through enhanced international cooperation in this regard."*
>
> *THE FUTURE WE WANT*, RIO+20, 2012

In 2013 the 14th meeting of the UN Open-ended Informal Consultative Process on Oceans and the Law of the Sea focused solely on ocean acidification. The Conference of the Parties (COP) of the CBD released in 2014 an update of its original review on ocean acidification, An updated synthesis of the impacts of ocean acidification on marine biodiversity was completed by 27 authors from 10 countries.

Links between the results of impacts on marine species and the economic worth of different sectors.
From IGBP, SCPO, IOC 2013.



Images: © iStockphoto.com

◆ Commercial value for fisheries represents the sum of capture fisheries and aquaculture in 2010 in US dollars. (FAO, 2012)

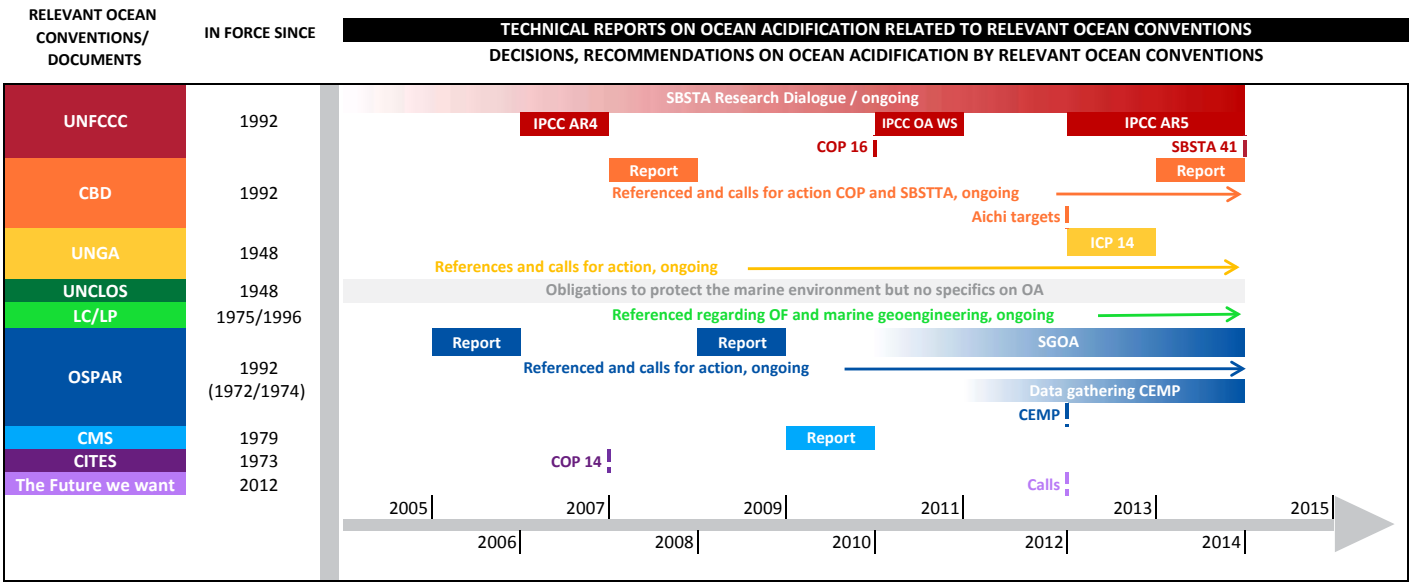
◇ Today's estimated value of global goods and services provided by coral reefs, such as coastline protection, tourism, biodiversity and food. (Cesar *et al.*, 2003; Costanza *et al.*, 1997)

△ Adapted from Wittmann and Pörtner, 2013. These data are for business-as-usual trajectories of CO_2 levels.

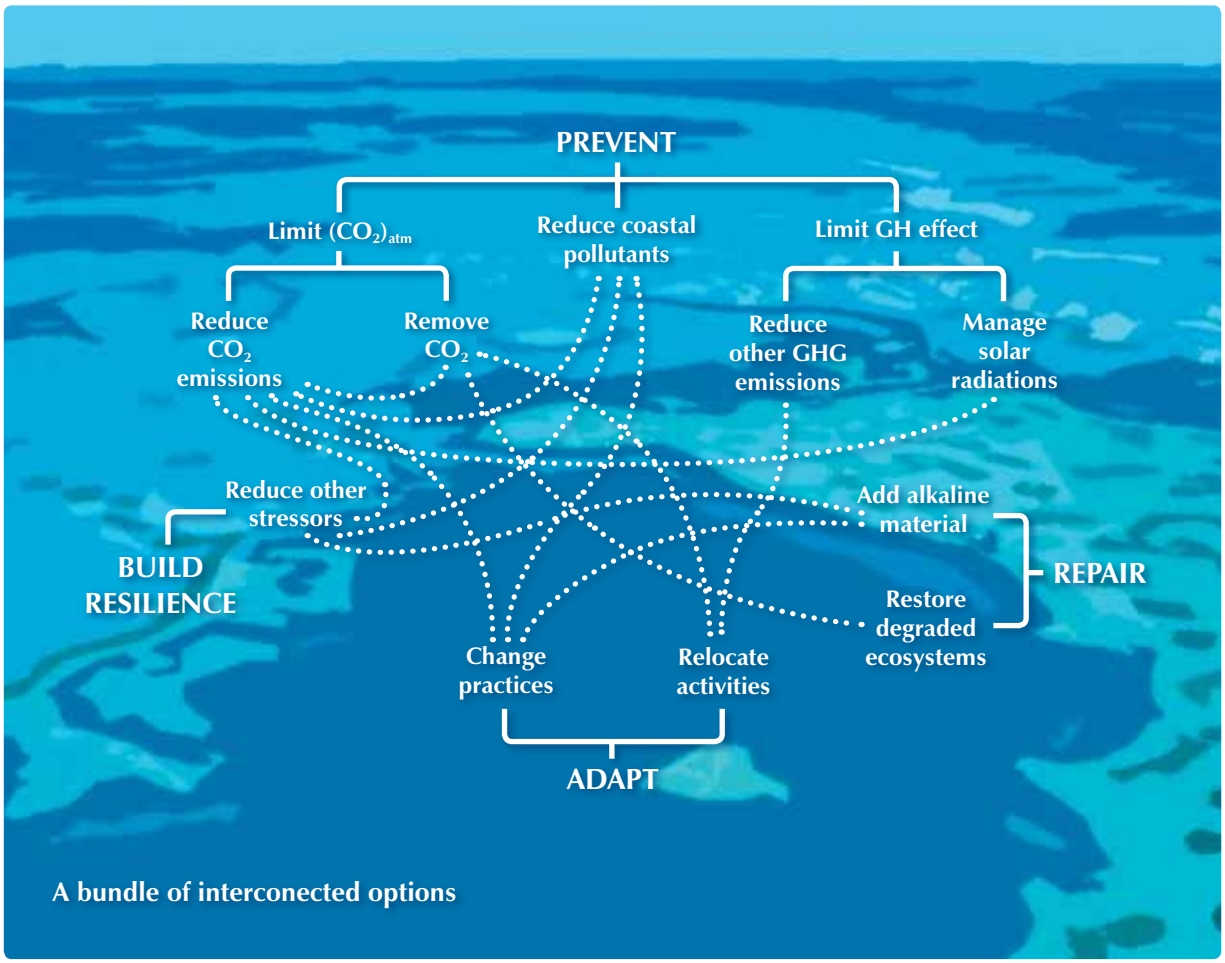
Ocean acidification is now also part of the UNEP 1st Global Assessment of Transboundary Waters. The following issues are due to be addressed:

- Ocean acidification indicators will target areas of concern related to ocean acidification and its impacts on coral reef ecosystems (tropical) and pteropods (polar region ecosystems).
- The report identifies priority areas for future Global Environment Facility (GEF) intervention and improved management, thus giving guidance for future project proposals to the GEF.
- Open Oceans Assessment: focused on themes where global commons/global environmental issues related to the ocean exist: climate, ecosystems/biodiversity, fisheries, pollution and ocean acidification.

The timeline: growing recognition at intergovernmental levels. Herr *et al*. 2014. Adapted from the original.



Areas of action that could be delivered through a suite of policy actions from global to local scales to help delay and manage the onset of ocean acidification. After Raphael Bille.



Where next with policy action?

Whilst intergovernmental organizations consider ocean acidification as a threat to the marine environment, urgent, more tailored international legislative action is required to mitigate, adapt and manage risks.

An optimist would look at past processes to tackle climate change through the UNFCCC and note that ocean acidification is merely the next step in a process that has built both in capacity but also complexity over the last 20 years:

- 1992 UNFCCC and goal to stabilize greenhouse gas concentrations.
- 1998 Kyoto Protocol and the reduction of CO_2 emissions by 5%.
- 2010 Cancún Agreement to limit warming to below 2°C.

As global ocean acidification, like warming, is caused by increased CO_2 concentrations, it would be logical to expect and require that the UNFCCC address ocean acidification and not just the current preoccupation on limiting warming to below 2°C to respond to its goal as described in Article 2:

> ***"...stabilization of greenhouse gas concentrations in the atmosphere at a level that would prevent dangerous anthropogenic interference with the climate system."***
>
> ***"...should be achieved within a time frame sufficient to allow ecosystems to adapt naturally to climate change, to ensure that food production is not threatened..."***
>
> *THE FUTURE WE WANT*, ARTICLE 2, RIO+20, 2012

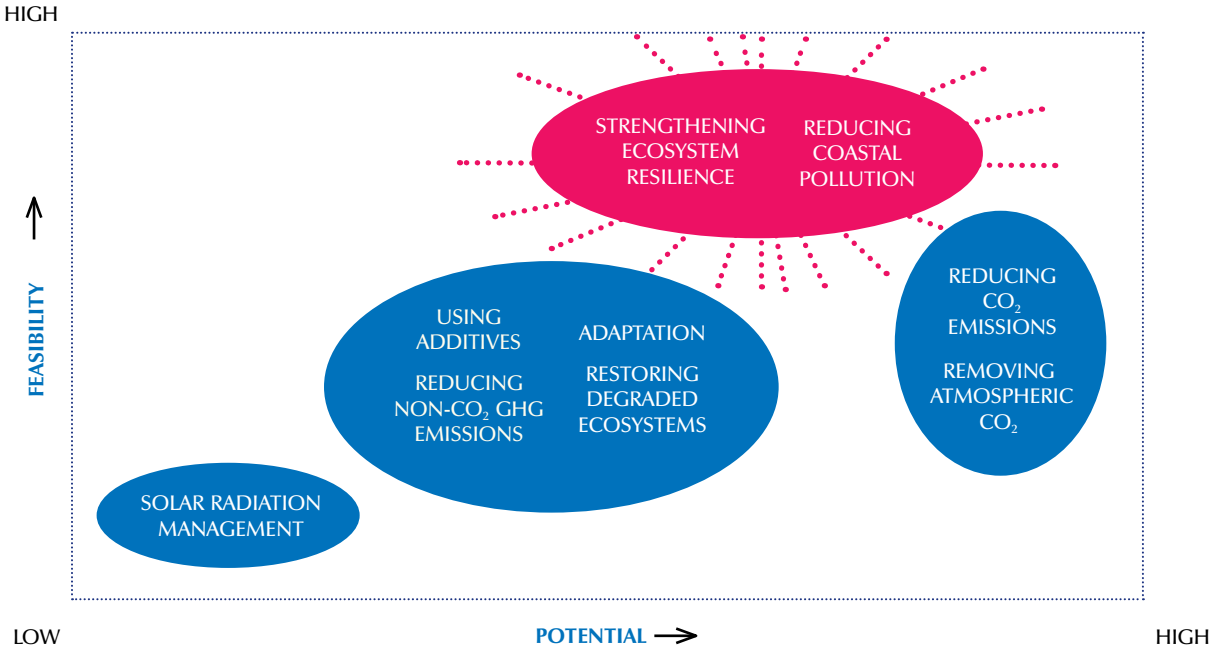
It becomes evident, however, that UNFCCC cannot be encapsulated by one single 'one-size-fits-all' climate target, or that if it does then the current emissions targets need significant tightening if they are to tackle the issue of ocean acidification.

So alongside climate policy, policy action also needs to be taken in a wide range of other fora, particularly the management of other stressors, such as coastal pollution, to build ecosystem resilience, to repair already deteriorated environments and to create appropriate adaptation mechanisms and increase ecosystem resilience. In essence there is a real discrepancy between appropriate and abundant legal frameworks that could address ocean acidification, and insufficient or inefficient enforcement of existing policies to carry this out.

Looking to the future

Despite the last decade of focused activities the impacts especially higher up in food chains are still poorly understood, it is still a largely 'invisible' problem with impacts that are likely to be highly uneven geographically and politically. Ocean acidification emerged as an issue after most options to respond to climate change had already been identified and tested. New tests are needed and a variety of responses are available to buy time while keeping the pressure on significantly reducing CO_2 emissions. Since solutions to ocean acidification cannot be viewed in isolation, it will be necessary to address a range of other stressors including warming of the ocean, deoxygenation, eutrophication, air pollution (e.g. NOx and SOx), overfishing, land-based sources of marine pollution, etc. The breadth of ocean and environmental treaties dealing with these issues need to account for the impact of ocean acidification and provide greater collaboration and knowledge exchange, at both international and national levels.

An attempt to compare the feasibility of different options to help address the onset of ocean acidification. After Bille *et al*. 2013.



Engaging new audiences

PARTICIPANTS AT THE SUNNYLANDS RETREAT agreed the need for a new 'blue alliance' of the concerned and vulnerable to ocean climate impacts, such as rising sea levels, and those exposed to ocean acidification, both now and in the future. http://www.sunnylands.org/news/view/733

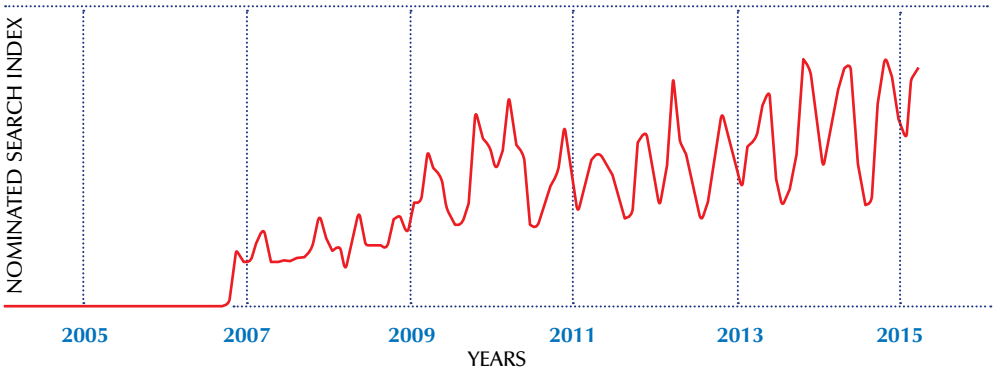
> *"We call on all governments, all sectors of society and communities to be part of the process."*
>
> HIS EXCELLENCY ANOTE TONG, PRESIDENT OF THE REPUBLIC OF KIRIBATI SPEAKING AT THE SUNNYLANDS RETREAT PRESS CONFERENCE

Over the past decade there has been an apparent dramatic growth in awareness of ocean acidification with Google searches on the topic increasing from just 17 'hits' in 2005 to well over 5 million in 2014. Whilst this is a significant increase the fact remains that relatively few people outside the science, policy and end-user communities have come in contact with ocean acidification or know much about this issue.

A survey in 2013/14 into public perceptions of ocean acidification in the UK suggests that four in five people have never heard of this issue and even those that were aware of it have a very low level of understanding. Initially most people surveyed did not express concern about ocean acidification, but when given some basic information they were much more concerned. It was concluded that there was an urgent need to further engage members of the public about ocean acidification through innovative communication channels. Regionally, for example in China, there is perceived to be greater awareness gauged by internet searches with perhaps a ten times increase in the past five years.

Google searches – an indicator of growing outreach and impact.

Updated from Turley and Boot 2011.



It is therefore critically important that further targeted communications, and through that, better public engagement is achieved especially with those that may be affected sooner rather than later by the consequences of an acidifying ocean. There is a need to move from outreach to relevant policy makers and decision-makers, which was essential in the early days of scientific discoveries on this issue but could be taken to characterize the last decade, to one where the strategy targets a broader spectrum of specific groups.

Looking to the future, work undertaken by the OAiRUG has identified seven key audiences who should form the focus for outreach in the coming years, as well as setting out ideas on ways to inform them, what information they may need, how this could be achieved, and any particular aspects that might be relevant to each audience. A snap-shot of what could be achieved in the next three years is highlighted in order to start a debate on increasing the effectiveness and speed by which we bring end user audiences up to speed on the challenges that lie ahead.

The seven key worldwide audiences whom it is important to inform on ocean acidification issues are:

- Regional ocean governance organizations
- The coral reef tourism industry
- The seafood industry and fishery dependent communities
- Climate negotiators
- Development banks and aid agencies
- The low carbon, low footprint energy community
- Foundations that fund ocean work

NEW AUDIENCES FOR OCEAN ACIDIFICATION INFORMATION

Whilst ocean acidification is recognized as a global issue, the impacts of an acidifying ocean are being, and will be felt, first regionally and locally. Already the shellfish aquaculture industry of the NW USA has experienced its impact and many other regions may follow. Ensuring that regional governance organizations, especially in areas predicted to be at risk and vulnerable, are well informed is a critical activity for the coming years. Partnerships between regional government, academics and industry have shown to be particularly successful at delivering knowledge transfer in the north-west USA.

The goal is to encourage the adoption of ocean acidification as an issue for local management in vulnerable areas of the ocean. To do this information on ocean acidification should be positioned and packaged to explain how it will or may affect the local community. This represents a shift from presenting a chemistry answer, to one that explains how lives may be affected and what actions can be taken to solve the problem.

The ocean acidification research community therefore needs to translate the science into an accessible format, creating user advice fact sheets on possible local actions and their likely effectiveness as well as highlighting the implications for ecosystem services and cultural heritage. Moreover, stronger linkage and inter-operability between information and practices at local through to global scales is needed. Global information is needed to provide context for local conditions, conversely a composite of local coastal conditions is needed to inform the global ocean acidification conditions.

Tropical coral reefs have been estimated to provide globally around $US 30 billion in net benefits each year. It is surprising then given the already significant risk that ocean acidification poses to the future health and stability of such reefs that the coral reef tourism industry does not seem to be strongly engaged (to date) in the debate on ocean acidification and the need to reduce carbon emissions.

The goal should be to encourage the coral reef tourism industry to become more aware of ocean acidification and its policy implications. To do this there is a need to support them to best understand reef resilience and through this to inform their investment decisions.

The ocean acidification research community should provide information to set this problem in the context of coral reef health, to explain the socio-economic consequences of inaction, and the risks for future health of reefs if significant decisions are delayed. A key part of this will be to find within the industry key champions and people who can serve as ambassadors for change.

Whilst it is still not clear what impacts ocean acidification will have on fish stocks it is quite clear that the potential for impacts of some other sectors of the seafood industry – such as mariculture – could be very significant. The risk to sustainability of local communities is real and may become increasingly problematic in the coming decades.

To better understand the situation the research community should support the industry in getting ahead of the problem of ocean acidification before impacts occur. They could do this by documenting the effects on production and helping the most vulnerable sectors of industry located in the most vulnerable areas of ocean adapt to the realities of an acidifying ocean. This is with the hope that they can then become ambassadors for the issue just as members of the shellfish industry have already done.

To do this, information will need to be provided on how the industry can actively participate in observations, monitoring and forecasting of effects, by explaining how they can adapt and mitigate to minimize impacts and who they can align and cooperate with in this venture. An important part of this will be to develop and disseminate monitoring standards, and over time develop thresholds in commercial and food species.

Actions under Article 2 of the UNFCCC have to date focused on mean global temperature change as a key threshold for setting emissions targets. However, the inclusion of ocean acidification as an issue of concern requires that greater attention is directly given to atmospheric carbon dioxide, with the possibility that even deeper emission cuts might be needed to avoid dangerous marine ecosystem impacts. There is therefore an urgent need to bring climate negotiators up to date on the latest evidence on ocean acidification.

The aim is to provide a clear scientific argument to help negotiators commit to tackling ocean acidification under the UNFCCC before the 2015 climate change conference in Paris (COP21). To do this the ocean acidification community needs to provide negotiators with the links and consequences between the likely commitments of Member States and the ocean acidification impacts that will result.

A rapid reaction from scientists to the contributions (INDCs – Intended Nationally Determined Contributions) that countries put forward in advance of COP21 to advise on those likely consequences would be very valuable.

Significant funding is required to address the economic implications of ocean acidification. One route to securing such support is by working more closely with development banks and aid agencies.

A key element of this is to connect and brief banks and aid agencies on the latest science and present predictions about vulnerable areas of the ocean and timescales by which impacts may be felt by local communities.

Greater clarity on the socio-economic consequences, and what can be done to alleviate these is urgently required.

The key end point for climate negotiations on ocean acidification is to significantly reduce the scale of anthropogenic carbon dioxide emissions which is driving further acidification of the ocean. It is therefore surprising that the industries that focus on emission reduction approaches to energy generation and provision have few visible links to the ocean acidification community. Such knowledge would support these industries in making stronger cases for why their technology should be adopted quicker than otherwise might be the case.

The key issue is therefore to bring the low carbon and ocean acidification communities together, to exchange information and to seek win-win situations. Not all low carbon industries have a small environmental footprint so a process of dialogue needs to take place to build a new set of ambassadors to help tackle ocean acidification.

A growing number of foundations and wealthy individuals are worried about environmental threats to the ocean. These funders take many different approaches, with some focused on specific geographic areas and others more broadly. Few currently fund ocean acidification work, while most have some focus on more well-known impacts such as the effects of fishing. Ocean acidification could overtake the ocean's ability to support local dependent communities and may affect ecosystems and species.

The goal is to undertake targeted outreach and communication to raise the profile of ocean acidification as a topic worthy of their investment. Information should be provided to help evaluate why they might prioritize ocean acidification and in such a way that they can gain insights into areas where funding is particularly needed within the subject area.

To fill this need the ocean acidification community should place their evidence in the context of the metrics that the foundations use – economics, human health and biodiversity – with a clear view provided on the provision of ecosystem services. One-to-one briefing packages should be created to this effect.

Ocean acidification and how it may affect vulnerable areas of the ocean does not respect nor recognize political boundaries or the economic status of the countries involved. It will affect undeveloped, emerging and developed economies alike and yet currently awareness and action is largely restricted to the G20 group of (developed) nations. Impacts are likely to be equally felt across the ocean but without significant action now to build new partnerships it is likely that the undeveloped and emerging economies that often have disproportionately large parts of the community dependent on seafood will be the worst hit and least able to adapt.

Steps are already being taken by the OA-ICC in the form of workshops in key regions but much more needs to be done to increase awareness, engagement and research. The development of ideas on forecasting ocean acidification for the coming decade by the OAiRUG in early 2015 will be vital for the UNFCCC, especially linked to its research and dissemination agenda under its technical and scientific advisory body SBSTA. This could also lead to a new political alliance of countries and states eager to cope with the effects of ocean acidification.

Measuring progress in tackling ocean acidification

EXCELLENCE IN COMMUNICATION will be key, as will the ocean acidification research community being clear on future priorities through a shared agenda of action and influencing. This action plan is a contribution to that process.

> ***"We have to ensure that oceans continue to meet our needs without compromising those of future generations. They regulate the planet's climate and are a significant source of nutrition. Their surface provides essential passage for global trade, while their depths hold current and future solutions to humanity's energy needs."***
>
> UN SECRETARY-GENERAL BAN KI-MOON 2014, WORLD OCEANS DAY MESSAGE

By all sectors working together it will be possible to increase grass-roots support that will be vital to deliver the action needed. Part of this may be through supporting the development of regional case studies as good examples of the threats posed by ocean acidification and potential responses, e.g. coral reefs in SE Asia; aquaculture in China, Pacific fisheries off South America.

Engaging with other bodies and activities, and getting clear and consistent OA messages presented to governmental and private sector stakeholders will be key. It is likely that much more extensive outreach will be needed especially with the audiences set out in this Action Plan.

Looking to the future, gauging the success or otherwise of such endeavours will be critical and developing ways to track progress will be important. Such success measures may include those listed here.

Ten measures of success in tackling ocean acidification

1. Ocean acidification being recognized as an important environmental issue by a wide range of countries (including BRICS and SIDS) in multilateral negotiations.
2. Key politicians make regular reference to need for action on ocean acidification (e.g. Re: energy policy).
3. Users of the sea adapting regionally to protect food supplies in an acidifying ocean (using experience from areas already impacted).
4. The dissolution of major biogenic reef habitats has slowed and damage to benthic and pelagic systems stays within reasonable limits.
5. More learning by doing –practical knowledge is being shared through effective connections between communities and decision-makers around the world.
6. More youthful participation in ocean acidification – for example on the OAiRUG, e.g. young charismatic scientists engaged from different disciplines and from all regions.
7. There is a step-change in investment in regionally-focused but globally-relevant observational science (developing local expertise).
8. There is a number of high profile ambassadors for action on ocean acidification.
9. There is greater confidence in projection of environmental, social and economic 'costs' of action and inaction to tackle ocean acidification, and these can be made real for people (without forgetting the uncertainties).
10. Many more people understand how ocean acidification will impact them, not just their grandchildren – and they are the ones that can make a difference.

Find out more

FAST-TRACK ACCESS to a selection of the latest literature and web links for key topics featured in the Monaco Ocean Acidification Action Plan.

Baird R, Simons M, Stephens T. (2009). Ocean Acidification: A Litmus Test for International Law. *Carbon & Climate Law Review* **4**:459.

Barnard N, Hain S. (2009). Impacts of ocean acidification on Marine Biodiversity. CBD Technical Series Report 46.

Billé R , Kelly R, Biastoch A, Harrould-Kolieb E, Herr D, Joos F, Kroeker K, Laffoley D, Oschlies A, Gattuso J-P. (2013). Taking Action Against Ocean Acidification: A Review of Management and Policy Options. *Environmental Management* **52**: 761-779.

Bopp L, Resplandy L, Orr JC, Doney SC, Dunne JP, Gehlen M, Halloran P, Heinze C, Ilyina T, Séférian R, *et al*. (2013). Multiple stressors of ocean ecosystems in the 21st century: projections with CMIP5 models. *Biogeosciences* **10**: 6225-6245.

Boyle A. (2012). Law of the Sea Perspectives on Climate Change. *The International Journal of Marine and Coastal Law* **27**:831-838.

Cesar H, Burke L, Pet-Soede L. (2003). The economics of worldwide coral reef degradation. Cesar Environmental Economics Consulting & WWF-Netherlands, Arnhem & Zeist, The Netherlands.

Costanza R, d'Arge R, de Groot R, Farber S, Grasso M, Hannon B, Limburg K, Naeem S, O'Neill RV, Paruelo J, *et al*. (1997). The value of the world's ecosystem services and natural capital. *Nature* **387**: 253-260.

Doney SC, Fabry VJ, Feely RA, Kleypas JA. (2009). Ocean Acidification: The other CO_2 Problem. *Annual Review of Marine Science* **1**: 169-192.

Feely RA, Sabine CL, Hernandez-Ayon JM, Ianson D, Hales B. (2008). Evidence of Upwelling of Corrosive 'Acidified' Water onto the Continental shelf. *Science* **320**: 1490-1492.

Gattuso J-P, Hansson L. (2011). *Ocean Acidification*. Oxford University Press.

Gattuso J-P, Bijma J, Gehlus M, Riebesell U, Turley C. (2011). Ocean Acidification: Knowns, unknowns and perspectives. In: Gattuso J-P, Hansson L. (eds) *Ocean Acidification* Oxford University Press pp.291-311.

Global Ocean Commission, November 2013. Policy Options Paper #2: Climate change, ocean acidification and geo-engineering.

Harrould-Kolieb ER, Herr D. (2011). Ocean acidification and climate change: synergies and challenges of addressing both under the UNFCCC. *Climate Policy* **12**: 378–389.

Herr D, Isensee K, Harrould-Kolieb E, Turley C. (2014). Ocean Acidification: International Policy and Governance Options. Gland, Switzerland: IUCN. iv + 52pp.

IAP. (2009). IAP Statement on Ocean Acidification.

IGBP, IOC, SCOR. (2013). Ocean Acidification Summary for Policymakers – Third Symposium on the Ocean in a High-CO_2 World. International Geosphere-Biosphere Programme, Stockholm, Sweden. http://www.igbp.net/publications/summariesforpolicymakers/summariesforpolicymakers/oceanacidificationsummaryforpolicymakers2013.5.30566fc6142425d6c9111f4.html

IPCC. (2014). Climate Change 2014: Synthesis Report Contribution of Working Groups I, II and III to the Fifth Assessment of the Intergovernmental Panel on Climate Change (Core Writing Team RK Pachauri and LA Myers (eds)). IPCC, Geneva, Switzerland. 151pp.

Kelly RP, Foley MM, Fisher WS, Feely RA, Halpern BS, Waldbusser GC, Caldwell MR. (2011). Mitigating local causes of ocean acidification with existing laws. *Science* **332**: 1036-1037.

Kroeker KJ, Kordes RL, Crim R, Hendriks IE, Ramajo L, Singh GS, Duarte CM, Gattuso J-P. (2013). Impacts of ocean acidification on marine organisms: quantifying sensitivities and interactions with warming. *Global Change Biology* **19**: 1884-1896.

Le Quéré C, Peter GP, Andres RJ, Andrew RM, Boden T, Ciais P, Friedlingstein P, Houghton RA, Marland G, Moriarty R, *et al*. (2013). Global Carbon Budget 2013. *Earth System Science Data Discussions* **6**: 689-760.

Newton JA, Feely RA, Jewett EB, Williamson P, Mathis J. (2014). Global Ocean Acidification Observing Network: Requirements and Governance Plan. http://www.goa-on.org/docs/GOA-ON_Plan_final_Sept_2014.pdf

Raven J, Caldeira K, Elderfield H, Hoegh-Guldberg O, Liss P, Riebesell U, Shepherd J, Turley C, Watson AJ. (2005). Ocean Acidification due to increasing atmospheric carbon dioxide. Policy Doc 12/05. The Royal Society, London.

Rayfuse R. (2012). Climate Change and the Law of the Sea. In Rayfuse R, Scott SV (eds), *International Law in the Era of Climate Change* Edward Elgar Publishers. pp. 147–174.

Rhein M, Rintoul SR, Aoki S, Campos E, Chambers D, Feely RA, Gulev S,. Johnson GC, Josey SA, Kostianoy A, *et al*. (2013). Observations: Ocean. In: *Climate Change 2013: The Physical Science Basis. Contribution of Working Group I to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* [Stocker, T.F., D. Qin, G.-K. Plattner, M. Tignor, S.K. Allen, J. Boschung, A. Nauels, Y. Xia, V. Bex, P.M. Midgley (eds.)]. Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

Riebesell U, Gattuso J-P. (2015) Lessons learned from ocean acidification research. *Nature Climate* **5**: 12-14.

Secretariat of the Convention on Biological Diversity. (2014). An Updated Synthesis of the Impacts of Ocean Acidification on Marine Biodiversity (Eds: S Hennige, JM Roberts & P Williamson). CBD Technical Series No 75 http://www.cbd.int/doc/publications/cbd-ts-75-en.pdf

Stern N. (2007). *The Economics of Climate Change: The Stern Review*. Cambridge University Press. Cambridge.

Stocker TF. (2013). The closing door of climate targets. *Science* **339**: 280-282.

Schubert R, Schellmhuber H-J, Bachmann N, Epiney A, Griesshammer R, Kulessa M, Messmer D, Rahmstorf S, Schmid J. (2006). The Future Oceans - Warming Up, Rising High, Turning Sour. GACGC, Berlin.

20 Facts about Ocean Acidification hyyp://www.oceanacidification.org.uk/pdf/OA20Facts11-18final.pdf

The Global Ocean Acidification Observing Network http://www.goa-on.org

The NOAA Ocean Acidification Program http://oceanacidification.noaa.gov http://www.pmel.noaa.gov/co2/story/Ocean+Acidification http://www.scor-int.org/HIgh-CO2_World%20Links.htm

Turley C, Boot K. (2011). The ocean acidification challenges facing science and society. In Gatusso J-P, Hanson L (eds) *Ocean Acidification*. Oxford University Press Chpt 13, pp249-271.

UNEP. (2010). UNEP Emerging Issues: environmental Consequences of Ocean Acidification: A threat to food security.

Washington State Blue Ribbon Panel on Ocean Acidification. (2012). Ocean Acidification: From Knowledge to Action Washington State Blue Ribbon Panel on Ocean Acidification Washington State's Strategic Response.

Washington Ocean Acidification Center http://coenv.washington.edu/research/major-initiatives/ocean-acidification/

Wittman AC, Portner H-O. (2013). Sensitivities of animal taxa to ocean acidification. *Nature Climate Change* **3**: 995-1001.

Online paper

DOWNLOAD a copy of this new paper on ocean acidification and learn more about this issue at: http://www.iaea.org/ocean-acidification/page.php?page=2198

What is the Ocean Acidification international Reference User Group?

OAiRUG
Ocean Acidification international Reference User Group

A KEY CHALLENGE is ensuring that ground-breaking science on issues such as ocean acidification addresses the questions that need to be answered and that these answers get quickly and effectively into the hands of policy advisers and decision makers so that action can be taken. The Ocean Acidification international Reference User Group (OAiRUG) draws on European and international experience in fast-tracking the exchange of information between scientists and end users.

The original RUG was established in 2008 to support the work of the European Project on Ocean Acidification (EPOCA), with subsequent support of complementary studies in Germany (BIOACID), the UK (the UK Ocean Acidification research programme, UKOA), the Mediterranean (the Mediterranean Sea Acidification in a Changing Climate (MedSeA)), and with strong links to similar processes in the USA and the Australian ocean acidification RUG. The OAiRUG draws together a wide range of end users to support the work of leading scientists on ocean acidification, to facilitate the rapid transfer of knowledge, and help the effective delivery of quality science.

This paper draws on the experience of the RUG, coupled with the knowledge of the leading experts on ocean acidification, to provide a strategic overview for policy advisers and decision makers on this critical and urgent issue.

Further details and contacts

FURTHER DETAILS on the work of the Ocean Acidification international Reference User Group and its membership can be found at: http://www.iaea.org/ocean-acidification/page.php?page=2198.

If you have any further enquiries please contact us at: danlaffoley@btinternet.com

Sources and contributors

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