An introduction to ocean acidification:

What it is, what we know, and what may happen.

Edited by Dan Laffoley, John M. Baxter, Carol Turley and Nelson A. Lagos

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Cover photo: Stakeholders and the public learning about the consequences of ocean acidification, Chile.
Photo credit: Nelson A. Lagos

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Photo credit: David Arnold, doublexposure.net / Marine Photobank

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Foreword

Ocean acidification is measurable and is already starting to cause economic problems and concerns in a number of countries. Only by planning ahead, monitoring our regional waters, creating forecasting capabilities and making the right types of investments now, can we improve our prospects in the future. Over time the problems can only increase and the number of affected regions and stakeholders will simply spread. Our current emissions of carbon dioxide have locked us into worsening conditions of ocean acidification for generations to come. Recovery of the ocean's chemistry will take far longer.

While governments work together to avoid the unmanageable by cutting carbon dioxide and solve the root cause of ocean acidification, regional action needs to be taken now to reduce local causes and manage the unavoidable consequences of past emissions. This will be a long-term process of investment in science, people and systems, but by acting now we will give ourselves more time to plan and adapt, all of which ultimately will reduce future social, economic and environmental costs to society.

We all need to work together to get ahead of the curve of progressive acidification. This document is based on materials developed by the Ocean Acidification international Reference User Group and other initiatives funded by my Foundation. I hope it stimulates discussion and more importantly action!

HSH Prince Albert II of Monaco

1. What is ocean acidification?

Over the last 200 years or so, widespread burning of fossil fuels, deforestation and cement production have released more than 500 billion metric tonnes of carbon dioxide (CO_2) into the atmosphere (about half of it in the last 30 years). This mass release of previously 'locked away' carbon enhances the natural greenhouse effect, and jeopardizes the future stability of the Earth's climate.

The ocean absorbs around 27% of the atmospheric CO_2 derived from burning fossil fuels and land use changes. As we have emitted more and more CO_2 into the atmosphere, the ocean has absorbed greater amounts at increasingly rapid rates. When the additional CO_2 released into the atmosphere dissolves in sea water, several chemical changes occur. These are collectively known as ocean acidification – also as the 'other CO_2 problem' and 'the evil twin of climate change'. The CO_2 dissolves in sea water to form carbonic acid, shifting the ocean chemistry towards more acidic conditions. These chemical changes are altering the system's ability to adjust to further changes in CO_2 that naturally occur over the millennia, significantly changing the chemistry of the seas, and leading to progressive acidification.

Over the last 200 years seawater acidity has increased by 30%. It should be noted that increasing seawater acidity lowers the ocean's natural 'basic' or 'alkaline' status and unnaturally forces the acid/base balance of sea water towards more acidic conditions. Future projections, if CO_2 emissions continue unabated (Business as Usual), show that by 2060, seawater acidity could have increased by 120%. To the best of our knowledge, the current rate of change is over 10 times faster than anything previously experienced in the last 55 million years.

Differing levels of confidence on the science around ocean acidification
Derived from *Summary for Policy Makers* IGBP, IOC, SCOR 2013.

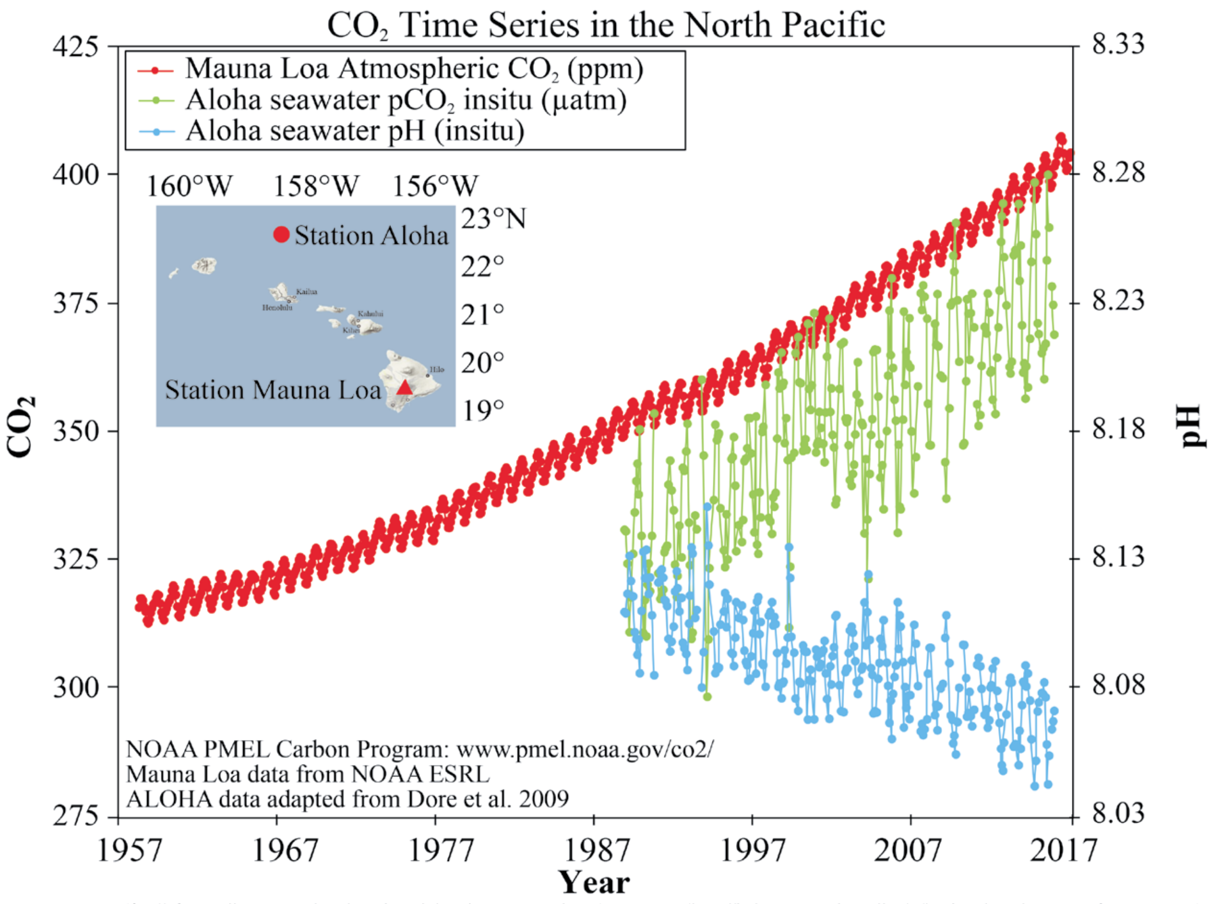
CONFIDENCE	SCIENCE
VERY HIGH	The capacity of the ocean to act as a carbon sink decreases as it acidifies
	Ocean acidification is caused by CO_2 emissions from human activity to the atmosphere that end up in the ocean
	The legacy of historical fossil fuel emissions on ocean acidification will be felt 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

2. How is ocean acidification different to climate change?

Ocean acidification has only recently received focused research, yet its implications may be as great as the global temperature increases arising from climate change. Indeed, whilst climate change may be diffuse and difficult to track, ocean acidification is measurable, predictable and progressive.

Ocean acidification is very different from climate change. Climate change is the consequence of a suite of greenhouse gases causing the Earth system to retain more of the sun's energy, typically referred to as global warming. Whereas ocean acidification is caused nearly solely by increased levels of atmospheric CO_2 dissolving into the ocean. Whilst there remains uncertainty about the impacts that will arise as a result of climate change, the chemical changes that are occurring in the ocean are certain and predictable.

The process of CO_2 dissolving in sea water is largely independent of climate change, although increasing seawater temperature reduces the solubility of CO_2[1]. Reducing the concentrations of other greenhouse gases will have no effect on ocean acidification other than helping reduce the overall temperature increase. Mitigating ocean acidification which is mainly driven by atmospheric CO_2 concentrations may accordingly require targets which differ from climate-mitigation targets, as impacts from ocean acidification may occur



Data: Mauna Loa (ftp://aftp.cmdl.noaa.gov/products/trends/co2/co2_mm_mlo.txt) ALOHA (http://hahana.soest.hawaii.edu/hot/products/HOT_surface_CO2.txt)
Ref: J.E. Dore et al., 2009. Physical and biogeochemical modulation of ocean acidification in the central North Pacific. *Proc. Natl. Acad. Sci. USA*, **106**:12235-12240.

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[1] But it is worth being aware that scientists expect possible feedback with climate change, e.g. by increased carbon input into coastal waters by increased run off and melting permafrost.

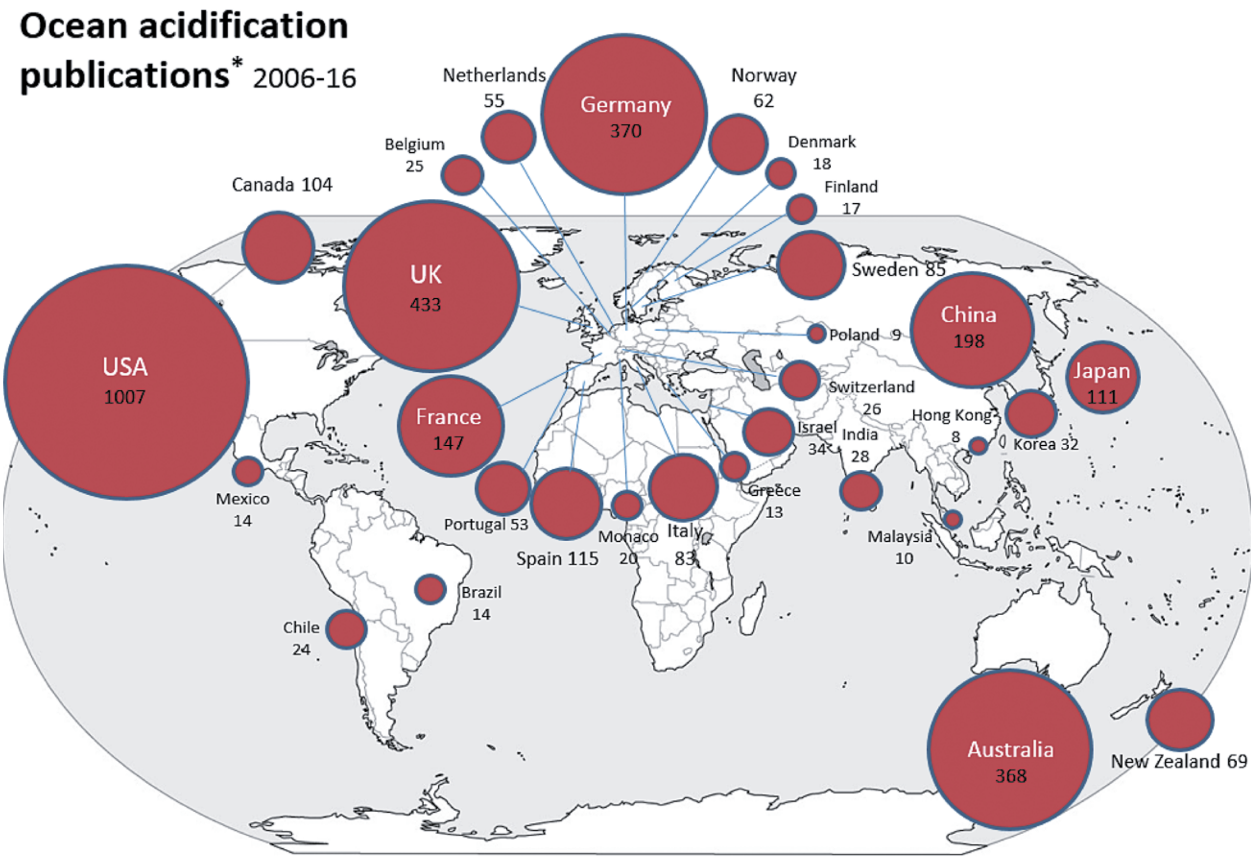
at different thresholds than broader climate effects in the atmosphere. Similarly, geo-engineering proposals to alter the atmosphere's radiation budget, making it more reflective, for example by putting sulphate particles into the upper atmosphere, will have no impact on atmospheric CO_2 levels and will not help to alleviate ocean acidification. However, active removal of CO_2 from the atmosphere would reduce ocean acidification.

There is very high certainty that seawater chemistry is changing due to rising atmospheric CO_2, and that human activities are the root cause. The strongest evidence is provided by detailed measurements in various parts of the world; for example, the 29-year record from the Pacific (off Hawaii).

Other long-term records around the world confirm the decline in ocean pH. Although there is high seasonal and even daily variability, depending on where you look, there is an unambiguous trend for increasing dissolved CO_2 in the upper ocean, whilst pH is falling. These trends closely match the changes in atmospheric CO_2 concentrations. More recently, with the development of coastal observations, the variability in pH in coastal waters has been found to be greater than the open ocean due to input of carbon and / or nutrients in run off from land.

3. Why are scientists worried?

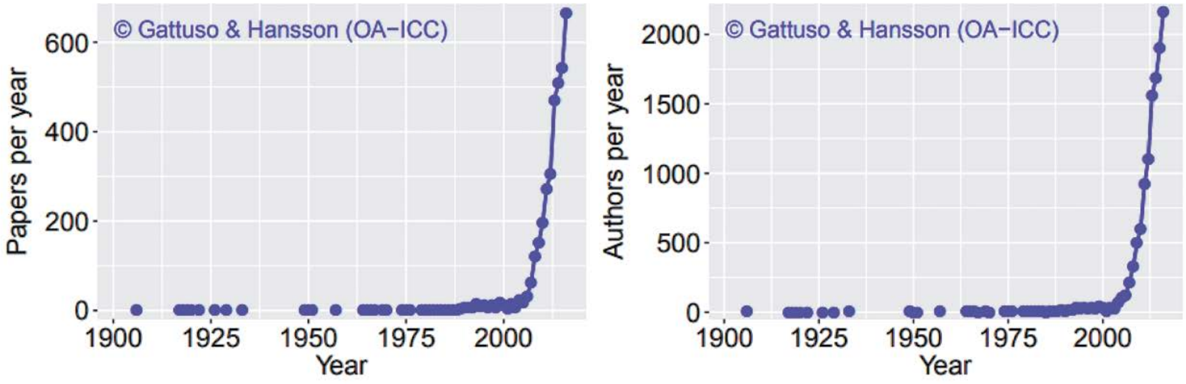
The science around ocean acidification is growing rapidly and results from recent research are changing our initial perceptions of the nature of possible impacts on ocean ecosystems. Most of the earliest experiments were 'short and simple' and showed considerable variability in results. Subsequently in the last decade there has been greater appreciation of the importance of experimental length, physiological condition and



Ocean acidification publications* 2006-16

*Data from Ocean Acidification International Coordination Centre (OA-ICC, hosted by IAEA in Monaco) based on first author address

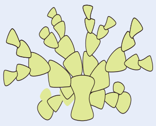
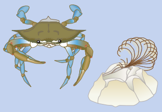
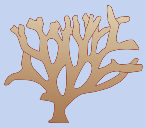
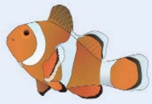
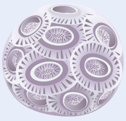
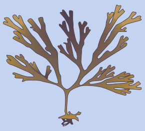
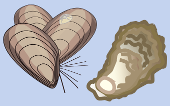
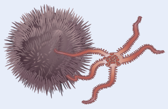
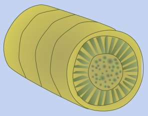
The annual number of peer-reviewed publications on ocean acidification and the number of authors involved, 1900-2016. Data from the bibliographic database of the IAEA Ocean Acidification International Coordination Centre (OA-ICC), updated from Gattuso and Hansson, 2011.



	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016
papers	23	19	32	62	122	151	197	273	305	471	510	542	665
authors	71	108	122	215	328	498	597	923	1103	1564	1683	1899	2167

interactions with other factors – providing a better understanding and hence improving our forecasting skill for 'real world' conditions. The increase in ocean acidification publications (and the number of countries and researchers involved) has been particularly dramatic since 2008, following the Second International Symposium on The Ocean in a High CO_2 World.

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	TAXA	RESPONSE	MEAN EFFECT
 Calcifying algae	Survival	⬜	 Crustaceans	Survival	🟨
	Calcification	🟨		**Calcification**	🟨
	Growth	⬜		Growth	🟨
	Photosynthesis	–28%		Development	🟨
	Abundance	–80%		Abundance	🟨
 Corals	Survival	🟨	 Fish	Survival	⬜
	Calcification	–32%		**Calcification**	⬜
	Growth	🟨		Growth	🟨
	Development	🟨		Development	⬜
	Abundance	–47%		Abundance	⬜
 Coccolithophores	Survival	⬜	 Fleshy algae	Survival	⬜
	Calcification	–23%		**Calcification**	⬜
	Growth	🟨		Growth	+22%
	Photosynthesis	🟨		Photosynthesis	🟨
	Abundance	🟨		Abundance	🟨
 Molluscs	Survival	–34%	 Seagrasses	Survival	⬜
	Calcification	–40%		**Calcification**	⬜
	Growth	–17%		Growth	⬜
	Development	–25%		Photosynthesis	🟨
	Abundance	🟨		Abundance	⬜
 Echinoderms	Survival	🟨	 Diatoms	Survival	⬜
	Calcification	🟨		**Calcification**	⬜
	Growth	–10%		Growth	+17%
	Development	–11%		Photosynthesis	+12%
	Abundance	⬜		Abundance	🟨

- ⬜ Not tested or too few studies
- 🟩 Enhanced <25%
- 🟨 No overall +ve or -ve response
- 🟪 Reduced <25%
- 🟥 Reduced >25%

Although it is difficult to precisely forecast the consequences of ocean acidification because there remain so many unknowns about human behaviour and ocean ecosystems' responses, we can learn from history what the likely possible outcomes will be, and we can look at areas of the ocean that have been subjected to natural long-term acidification. Communities of organisms found at cold water volcanic CO_2 vents on the sea floor (not the extremely hot deep-sea vents) with lower pH, similar to that predicted for the next few decades, show that certain species of microalgae, seaweeds and seagrasses can grow very well in such areas, but in comparison to other similar areas, not subject to reduced pH levels, overall biodiversity is reduced, and shell corrosion is evident.

It can be expected that as seawater pH and carbonate levels continue to fall there will be 'winners' and 'losers' in ocean ecosystems, but it is inevitable that marine communities will change. The animals and plants most likely to be affected first are those that have calcium carbonate-based shells or skeletons. Organisms can respond to harmful changes in their environment in one of four ways: they can migrate, adapt, evolve or die.

The key question is not whether ocean life on the whole can migrate, adapt, and / or evolve in response to ocean acidification, but its ability to respond quickly enough in the face of 'rapid' ocean acidification and to do so in such a way that the 'new' communities that arise provide the same essential goods and services that we use and that support us. Even migration for some species could be difficult, especially sedentary ones, it would mean that their free-floating early life stages would need to travel to new locations where there is space to settle and the right conditions to flourish. But these larvae are known to be particularly sensitive to ocean acidification and this may not be viable in any event.

It is the first time since modern-day humans have been on Earth that we have dramatically altered the fundamental chemistry of such a large part of the global ecosystem. We are in effect conducting an experiment on a planetary scale that takes us into uncharted territory that will require immense effort and resolve for it to be reversed.

4. What do we know?

We now know that very many species of ecological, commercial and cultural importance are likely to be adversely impacted either directly by ocean acidification or indirectly via altered food webs and habitats. However, the response varies greatly between species, and some species may be positively affected; furthermore, responses can vary over time through acclimation and multi-generational adaptation. Thus there remains considerable uncertainty regarding the overall long-term impact at the ecosystem scale.

Combining the results from the very many laboratory experiments shows that significant negative effects include reduced survival, impaired calcification, slowed growth and development, altered behaviour and predator-prey interactions, and decreased abundance. Positive effects (e.g. arising from enhanced photosynthesis or loss of competitors and predators) 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.

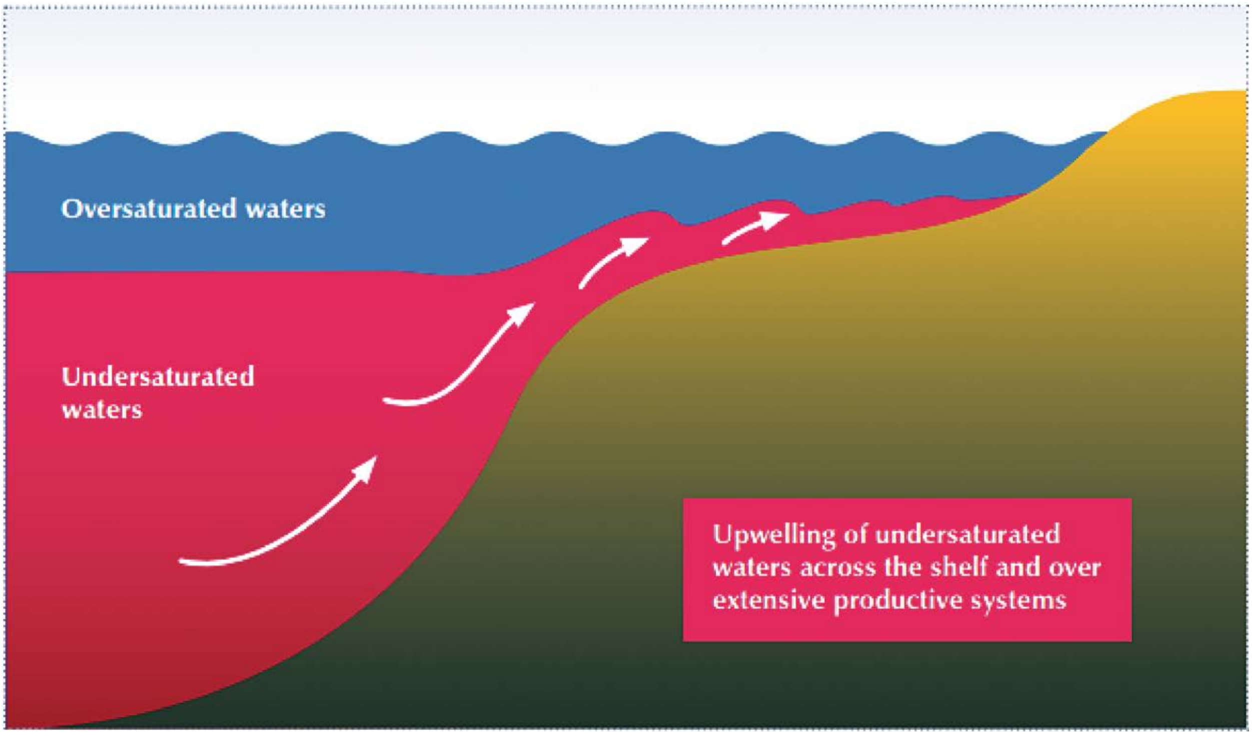
Ocean acidification is not only progressively decreasing the ability of many organisms to build their shells and skeletons, but will also progressively affect ecosystems' structure and function. Ocean acidification could trigger a chain reaction of impacts through the marine food web by the reduction or even loss of species that are key links in the food web from smaller organisms to those larger ones at the top of the food web. Sea butterflies (pteropods), small swimming snails, are a good example of a group of organisms that are sensitive to ocean acidification and are an important food for many fish, birds and whales. Some shellfish are sensitive and particularly vulnerable too, and ocean acidification is already adversely impacting multi-million-dollar oyster hatcheries off the west coast of the US. Some larval fish may be also vulnerable in the future which when combined with the susceptibility of shellfish could threaten the food security of many of the hundreds of millions of the world's poorest who depend on the sea for their main protein source. Most regions of the ocean will become inhospitable to coral reefs thus affecting food security, tourism, shoreline protection and biodiversity. As acidity and sea temperature increase, the ocean's ability to continue to absorb atmospheric CO_2 will be reduced, thus exacerbating the rate of climate change.

Whilst ocean acidification will occur everywhere, it will be more intense in some parts of the world than others, and impacts will also vary, because of differences in temperature and circulation patterns. Carbonate levels in sea water which are presently high enough to allow calcium carbonate structures like shells and skeletons to stay intact (i.e. 'oversaturated' conditions), can drop to levels that will mean these hard structures will begin to dissolve (i.e. 'undersaturated' conditions).

Model-based projections show that the Arctic Ocean will be first to cross this ocean acidification-related chemical threshold, when waters change from oversaturated with calcium carbonate to undersaturated. If levels of atmospheric (and oceanic) CO_2 continue to rise at current rates, then by 2018 it is projected that around 10% of the Arctic Ocean will have crossed this threshold, rising to one-half of the Arctic Ocean by 2050. By 2100 it is likely that the entire Arctic Ocean will be undersaturated. Recent observations confirm that undersaturation is already occurring but faster than expected in the western Arctic waters.

Other hot spots of immediate concern are coastal regions which periodically experience upwelling events where deeper ocean water circulates onto continental shelves and near-shore areas. This exposes productive upper ocean ecosystems to colder water containing more nutrients but also more CO_2. As ocean acidification progresses, the upper level of the oversaturated layer of sea water becomes shallower each year; these natural upwelling events will more often result in undersaturated water affecting the surface layers. Coastal marine organisms that form shells are unaccustomed to such events, and periodic exposures to these significantly different conditions may affect these communities. Upwelling of undersaturated water is already occurring on the west coast of North and South America, and it may start to occur elsewhere where ocean conditions allow.

Seasonal invasion of undersaturated waters such as is already occurring on the west coast of North America could have serious impacts on important fisheries such as the oyster industry.
Source after Carol Turley based on Feely *et al., Science, 2008.*



5. Ocean acidification is not the only climate-related stressor

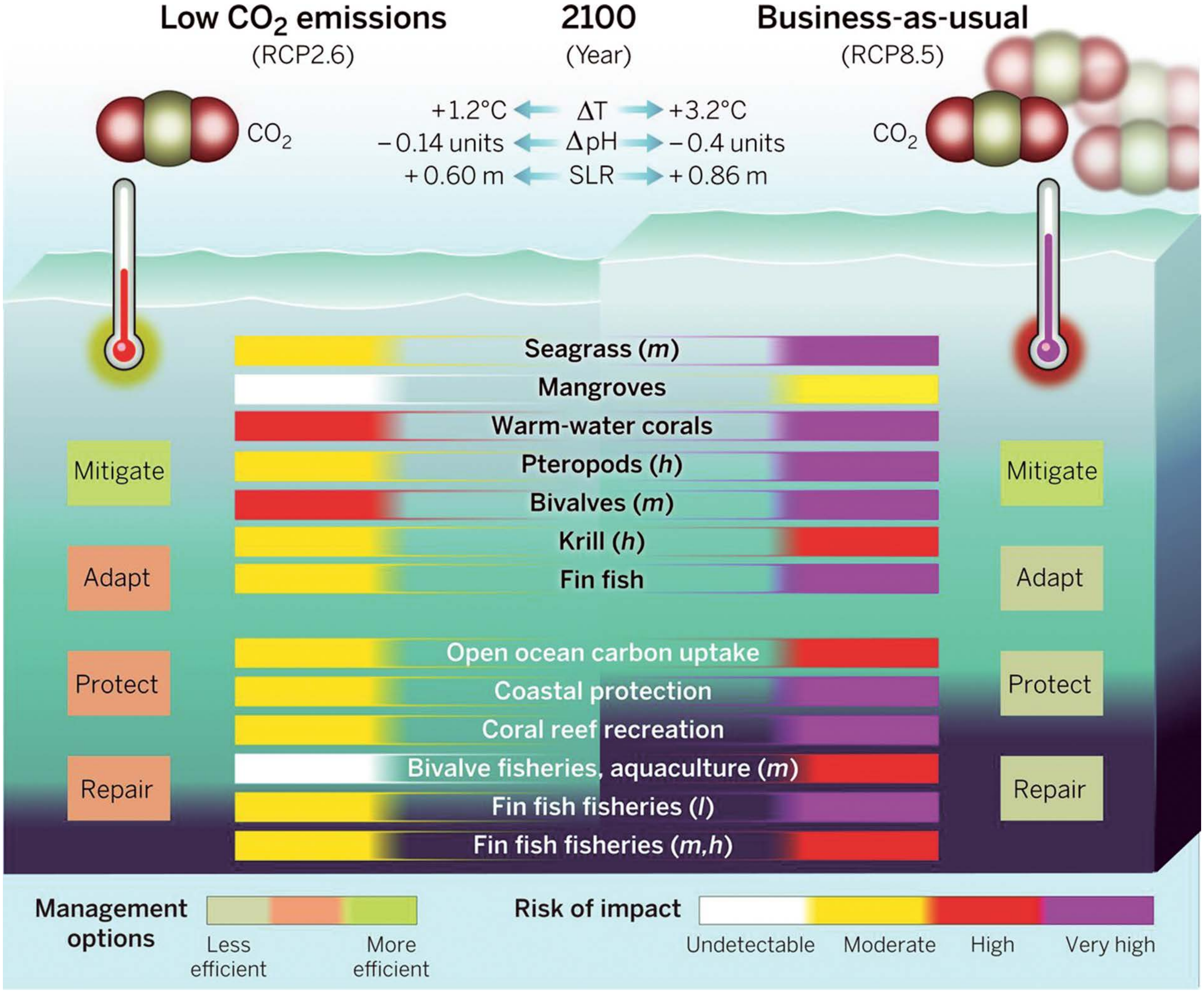
The ocean has absorbed over 90% of Earth's additional heat since the 1970s, but this has led to ocean warming and decreasing oxygen content (due to reduced oxygen solubility caused by warming and decreased supply to the ocean interior due to less mixing).

There has already been a mean global sea surface warming of about 0.83°C and this is likely to increase in some ocean regions as greenhouse gases in the atmosphere increase. Less mixing in a warmer ocean, particularly in the tropics, means there will be less nutrients being brought from nutrient-rich deeper waters to the nutrient-poor surface waters. As this process drives ocean productivity this could significantly diminish fisheries in these regions. Warming water also has direct effects on the physiology of marine organisms and is resulting in a geographical shift of some species towards cooler waters.

As fish and many other marine organisms depend on oxygen to function, a decline in the oxygen concentrations will add to their physiological stress while expansion of zones of very low oxygen levels may result in their exclusion from these regions.

Ocean acidification, warming and decreasing oxygen levels each stress marine organisms, and in some regions marine life may experience more than one of

Changes in ocean physics and chemistry and impacts on organisms and ecosystem services according to stringent (RCP2.6) and high business-as-usual (RCP8.5) CO_2 emissions scenarios. From Gattuso *et al.*, 2015.

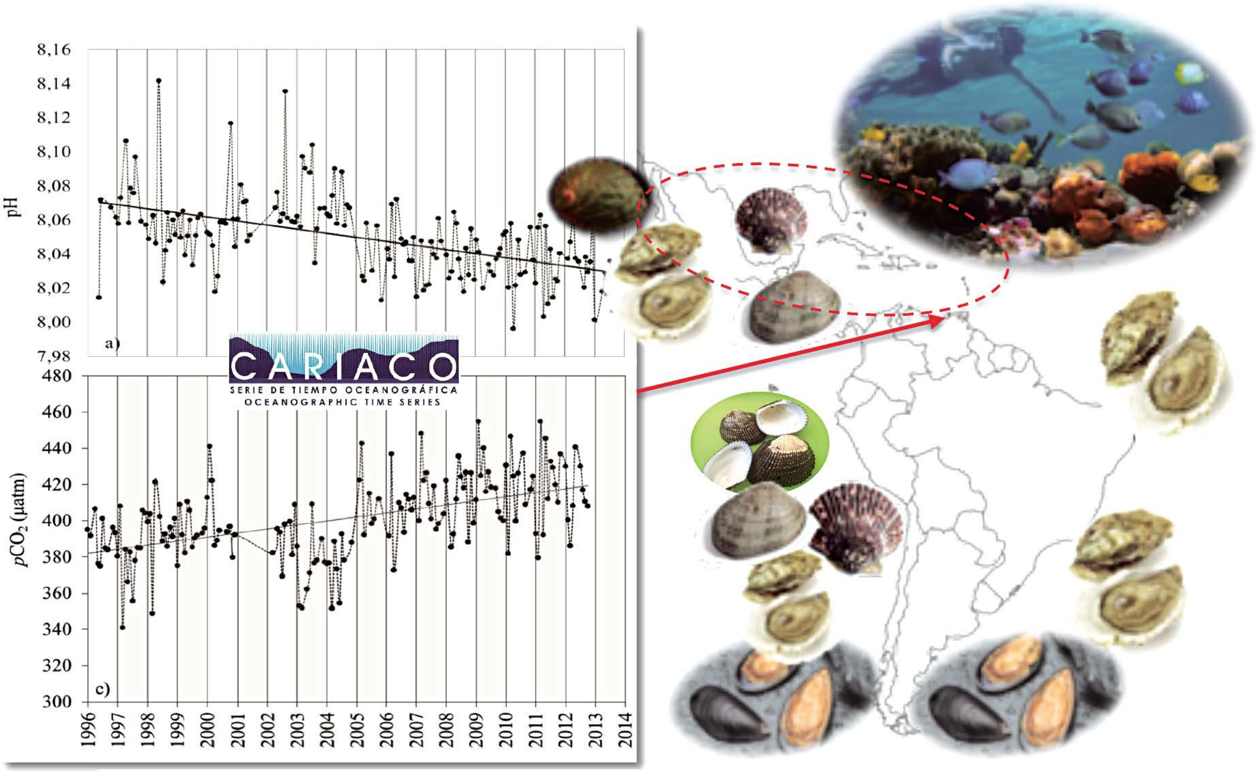


these at the same time. Acting together, these stressors could increase the threat to marine life and the goods and services they provide compared to one stressor acting on its own although the interactions are likely to be complex and are not yet fully understood. There is increasing evidence that a high CO_2 emissions scenario (consistent with Business as Usual) will rapidly and significantly alter many ecosystems and food webs through one or more of these stressors, and that they represent a high or very high risk to fin fisheries and shellfish aquaculture in vulnerable regions. A low CO_2 emissions scenario (consistent with Paris Agreement of keeping global temperature increase below 2°C) reduces the risk considerably but not entirely; for example, risk to coral ecosystems even under the low emissions scenario remains high. This means that while urgent emissions reduction is essential, adaptation is also important.

6. How could it impact our region?

Latin America and Caribbean shores encompass examples of all the ecosystems and marine resources that are vulnerable to the impacts of ocean acidification. The structure and function of rocky and sandy shores, estuaries, mangroves, coastal lagoons, seagrass meadows, saltmarshes, and fjords among others, are modulated by key ecological processes that provide essential habitat for critical life stages of marine organisms. In these ecosystems, the impacts of ocean acidification could be exacerbated by local factors. For instance, throughout the Caribbean islands, carbonate saturation state in sea water, a chemical condition necessary to build, for example, coral skeletons, has declined by ca. 3% per decade. This, coupled with a decreasing trend in the pH levels for the last 20 years, suggests that the impacts on marine calcifying organisms and ecosystems are already occurring in the region. Coral reefs are widely distributed throughout the Caribbean Sea and the shores of the Gulf of Mexico representing an important hot spot of biodiversity

Temporal trends in pH and $p\text{CO}_2$ recorded by the Cariaco Programme, vulnerable marine resources (abalone, oyster, scallops, mussels) and the regional distribution of coral reefs (ellipse) along the shores of Latin-America and Caribbean are also illustrated



Astor et al. 2017. Mem. Fund. La Salle de Cienc. Nat. 181–182 and provide a variety of ecosystem services such as fisheries and tourism for coastal communities. Reduced calcification of the coral skeletons as a result of ocean acidification will decrease the structural integrity of the reefs, making coastal communities increasingly vulnerable to wave exposure and storm surge.

Along the western margin of South America, coastal upwelling of the Humboldt Current enhances productivity and sustains one of the most productive and important fisheries and aquaculture industries on the planet. Mexico and most countries of Central America have fisheries activities both on the Pacific and Caribbean coasts. The landings recorded for the coastal fisheries operating in Latin America and the Caribbean show downward trends during the last two decades. At the same time, the region accounted for 3% of the 1.8 million tonnes of global aquaculture production, an activity that showed an important growth in the last decade. Small-scale aquaculture is still practised by more than 100,000 families in the countries of the region. Chile, Brazil, Ecuador and Mexico are known for their aquaculture production, much of which is based on species such as mussels, scallops, shrimps, oysters and clams. In general, coastal communities in these countries are highly dependent on small-scale fisheries and aquaculture production especially as a source of jobs and food.

In the upwelling region of northern Chile, ocean acidification and cold temperatures have led to reduced shell calcification and a 25% reduction in the growth rate of cultured scallops. While in Chile, there is some capacity to produce scallops under hatchery conditions, in Perú, scallop aquaculture relies on the availability of seed from natural stocks which are highly dependent on environmental conditions, and which are regularly threatened by acidification and cold temperatures in upwelling regions. Studies also indicate that biomass production of mussel aquaculture will be reduced by between 20 - 30% by ocean acidification in the Patagonian waters where both small and industrial scale farming depends on the seed provision from natural stock. Both upwelling regions and Patagonian waters are naturally rich in CO_2 and already have ocean pH that is projected for the open ocean by the end of the century. Thus, as atmospheric CO_2 increases, its absorption by these waters will progressively exacerbate the impacts of ocean acidification in the region. Thus, the adaptability of these socio-ecological systems relies on their capacity to switch between target species, gear types and cultivation strategies. But if the species involved are vulnerable then that capacity to switch will be greatly reduced especially if the natural stocks become depleted under stressful conditions imposed by ocean acidification.

The impacts of ocean acidification would alter the amount, composition and distribution of the resources available to fisheries and aquaculture activities. In addition, these impacts will be concomitant with the occurrence of other climate-stressors such as warming, hypoxia and sea-level rise in the region. These stressors in combination may affect coastal infrastructure on the Caribbean coast, and thus could lead to an increase in the cost of production, processing, and distribution of food. Finally, these impacts will also occur alongside regional overfishing, reduced environmental quality and increased social and economic pressures upon marine resources and ecosystems of Latin America and the Caribbean.

7. What can we do about it?

Ocean acidification must be recognized for what it is: a global challenge of unprecedented scale and importance. Now is the time to act on ocean acidification and the target for action must be to reduce and ultimately reverse the rapid increase in atmospheric CO_2 and limit future levels. There is, however, a lag between reduced CO_2 emissions and a reversing of acidification. In other words, acidity in the ocean will continue to increase for some years after CO_2 emissions have been reduced. This puts a premium on early emissions cuts and a penalty on delaying making significant cuts in emissions. Reducing the emissions of CO_2 from the burning of fossil fuels, cement manufacturing and deforestation are the only realistic ways of beginning to achieve such a reduction. We also need to protect, conserve and enhance natural carbon sinks and stores on land and in the ocean to prevent more CO_2 reaching the atmosphere and therefore the ocean.

There are no practical solutions to remediate ocean acidification once it has occurred and we may have to rely on nature to take its course. This will inevitably be a long-term recovery process that could take 10,000s of years for the ocean to be restored to its carbonate equilibrium, with biological recovery taking perhaps even longer. Mitigating ocean acidification can only be done through a real, sustained and substantial reduction in emissions to stabilize atmospheric CO_2 levels, through cuts in emissions, and by application of technologies that actively removes CO_2.

In support of global action on emissions there is also a range of regional and local measures that should be undertaken to sustain and recover ocean health. The severity of ocean acidification impacts is likely to depend, in part, on the interaction of acidification with other environmental stressors, such as rising ocean temperatures, decreasing oxygen levels, over-fishing, and land-based sources of pollution. We need to identify any regions of the ocean that seem most resilient to acidification. We need to ensure through good management and protection that the resilience of such areas is maintained or restored to create future refuges. For broad areas of the ocean we similarly need to look at ways to increase the resilience of ecosystems to withstand the pressures that ocean acidification and the other climate stressors will impose, so they have the ability to resist change and to recover more quickly.

8. Ten Monaco priorities to address ocean acidification

- Shift the emphasis of scientific research from individual species to ecosystems, in order to understand impacts on interspecific interactions and food webs and to assist the parameterization of models.

- Devise long-term experimental studies to understand adaptation as well as acclimation.

- Consider multiple stressors, and natural variability to gain better confidence of future impacts under ‘real world’ conditions.

- Support efforts to reduce anthropogenic CO_2 emissions at sufficient scale and speed to avoid dangerous climate change and dangerous ocean acidification.

- Invest in prudent adaptive marine management approaches to best manage carbon sinks, to foster greater ecosystem resilience and protect genetic diversity, as well as communicating local and regional success stories on adaptation.

- 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 on the spatial and temporal scales required for decision making.

- Increase international collaborative coordination efforts that support national research programmes, that maintain standards, openly shared data, support effective deployment and interpretation of monitoring efforts and that enhance communication with stakeholder communities.

- Identify and develop relationships with new stakeholders that are likely to be affected by ocean acidification.

- Support research to map the current and projected economic impacts of ocean acidification to assist in the identification of local and regional examples of impacts.

- Invest in education and communication, aimed at a wide public audience, policy makers, and scientific training to support capacity development in vulnerable regions that currently lack such capabilities.

9. Taking action on ocean acidification at the local level

There are several ways to act and help combat ocean acidification:

Join

International scientific and policy networks exist which can help expand your knowledge about ocean acidification and its specific impacts to your country and region. The Global Ocean Acidification Observing Network (www.GOA-ON.org) was founded five years ago as an effort to expand access to ocean acidification data, both how the chemistry of the ocean is changing and how marine ecosystems are being affected, through scientific capacity building and development of best practices. Consider becoming a network member by filling out some information on the GOA-ON website which will then provide you with access to various training, mentoring and data sharing opportunities. Also consider joining the Latin American Ocean Acidification (LAOCA) regional network within GOA-ON. In addition, check out the International Coordination Centre on Ocean Acidification , overseen by the IAEA, which provides daily information about the most recent scientific findings and other news coverage on ocean acidification. You can quickly sign up to receive these emails.

Fund

Scientific research to better understand the risks posed by ocean acidification to marine resources and human communities which rely on them is not inexpensive. National governments, non-governmental organizations, private foundations and individual donors are stepping up to contribute to the global OA scientific effort. In the US, the Ocean Foundation announced the creation of the Friends of GOA-ON, a public-private partnership which enables pooling of funding from a variety of sources focused on expanding scientific capacity around the world. To date, they have received funding from the US Department of State, the Government of Sweden, private donors and several US foundations to further training and the provision of scientific kits in Africa, the Pacific Islands and the Caribbean.

Collaborate

We can move forward faster together. LAOCA is a network of 36 scientists from eight Latin American countries. Scientists in the network have published more than 120 publications and have helped train 48 graduate students. LAOCA is also networked with the broader Global OA Observing Network which is seeking to provide direct access to OA data from Latin America. Only by combining data gathered from around Latin America into a broader global ocean context, can we begin to understand current and future local impacts of ocean acidification. For instance, scientists in Chile are now working with the shellfish industry to overcome OA-related water quality impairments affecting their important scallop industry. Much of this work is informed by experience from the United States west coast which has also experienced difficulties in the past decade rearing shellfish larvae due to OA.

Monitor

What we don't measure, we cannot manage. As ocean acidification monitoring in coastal regions has expanded over the past decade, we now understand that the carbonate chemistry of coastal regions, which is highly influenced by people, is so variable that detecting the unique impact of ocean acidification is extremely tricky. Run-off from land, fishing, and temperature change due to climate change are other stressors in coastal waters. Therefore, measuring carbon chemistry at higher spatial scales in coastal waters is necessary. In addition, determining aspects of the marine ecosystem which are uniquely affected by OA and then measuring changes over time are needed across Latin America. Using the guidance from GOA-ON and working within the framework of LAOCA would be highly recommended.

Communicate

As knowledge is gathered, it is imperative that we communicate the results widely. Too few people understand the risks posed by ocean acidification to their livelihoods. Once informed, people are generally willing to take actions to mitigate (reduce CO_2) or adapt (reduce stress on marine ecosystems). It is imperative that we spread information about what we know about ocean acidification to a wide audience. In the US and Europe, we have developed some effective messages and tested them with a variety of audiences. Please check out the resources listed below for more information. By communicating messages about ocean acidification to high level policymakers, we can also reinforce that the reduction in CO_2 emissions which is the most important action that can be taken to reduce the impact of future ocean acidification.

Adapt

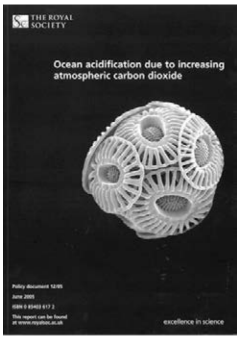
Communities directly affected by ocean acidification are already exploring various options for “OA-proofing” their livelihoods. Shellfish hatcheries in the US and Chile now use observing technologies and addition of buffers to protect shellfish larvae from OA when the larvae are most sensitive, bringing industries on the verge of collapse back to health. Scientists are exploring how to breed more resistant oysters, clams, abalones and even corals. Other scientists are exploring whether the use of kelp and other macroalgae can pull CO_2 out of the water, thus creating a healthier environment for the growing of shellfish. Adaptation strategies need to be tested scientifically and shared when proven successful.

Finding out more about ocean acidification – useful sources of further information

The Ocean Acidification International Coordination Centre has news updates and other useful information on ocean acidification: https://www.iaea.org/ocean-acidification/page.php?page=2181

The Global Ocean Acidification Observing Network has membership around the world and you can join too: http://www.goa-on.org/GOA-ON.php

Ocean acidification was featured as a new topic in the press release from the first global meeting on the Ocean in a High CO_2 World in 2004. Since then, a rapid expansion in work and concern on this issue has occurred. A selection of key reports that together provide a comprehensive source of knowledge are as follows:



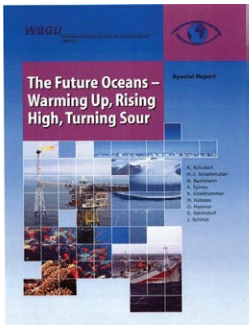
THE ROYAL SOCIETY

Ocean acidification due to increasing atmospheric carbon dioxide

Policy document 12/05
June 2005
ISBN 0 85403 617 2
This report can be found at www.royalsoc.ac.uk

excellence in science

The first major publication on ocean acidification rapidly followed. The Royal Society 2005 policy document *Ocean acidification due to increasing atmospheric carbon dioxide* recognized ocean acidification is a significant threat to many calcifying organisms with the potential to alter food chains and other ecosystem processes and lead to a reduction of biodiversity in the oceans. The appointed working group made specific policy recommendations, including limiting the accumulation of CO_2 emissions to avert impending damages from ocean acidification.

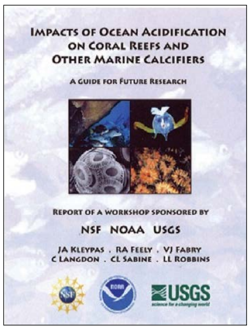


WBGU

The Future Oceans – Warming Up, Rising High, Turning Sour

Special Report

In 2006 the German Advisory Council on Global Change released *The Future Oceans – Warming Up, Rising High, Turning Sour*. This document presents the hazards of acidification within the context of other climate change processes in the ocean. Policy makers were urged to acknowledge the role of CO_2 as an ocean hazard during future negotiations under the United Nations Framework Convention on Climate Change.



IMPACTS OF OCEAN ACIDIFICATION ON CORAL REEFS AND OTHER MARINE CALCIFIERS

A GUIDE FOR FUTURE RESEARCH

REPORT OF A WORKSHOP SPONSORED BY

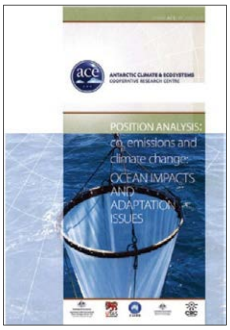
NSF NOAA USGS

JA KLEYPAS . RA FEELY . VJ FABRY
C LANGDON . CL SABINE . LL ROBBINS

USGS

Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research came from a joint effort by NSF, NOAA and USGS. This is a 2006 summary report on the state of the science regarding the biological consequences of acidification, particularly as they affect calcifying organisms. The report concludes with a recommended research agenda and underscores the need for research to place the long term biological changes induced by acidification into a historical context.

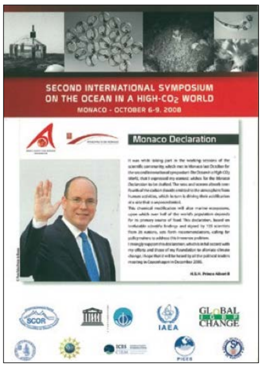
The U.S. Ocean Carbon and Biogeochemistry Program (OCB) sponsored a workshop in conjunction with NOAA, NASA and NSF to develop a U.S. research strategy. Around 100 scientists developed a plan to investigate the impacts of ocean acidification on four marine ecotypes: coral reefs, coastal margins, tropical-subtropical open ocean systems, and high latitude regions. The recommended research was reported in 2008 in *Present and Future Impacts of Ocean Acidification on Marine Ecosystems and Biogeochemical Cycles.*



ANTARCTIC CLIMATE & ECOSYSTEMS COOPERATIVE RESEARCH CENTRE

POSITION ANALYSIS: CO_2 emissions and climate change: OCEAN IMPACTS AND ADAPTATION ISSUES

Also in 2008, a significant policy document was provided for the Australian government: *Position Analysis: CO_2 Emissions and Climate Change: Ocean Impacts and Adaptation Issues.* This document sought to describe the process of acidification, outline the biological and human effects and to advise the Australian government on issues relevant to policy development. It was accompanied by a one page fact sheet *Ocean Acidification: Australian Impacts in the Global Context* that discussed ocean acidification in terms of the science: what is known, what needs to be known and what can be done.



SECOND INTERNATIONAL SYMPOSIUM ON THE OCEAN IN A HIGH-CO_2 WORLD

MONACO - OCTOBER 6-9, 2008

Monaco Declaration

In 2009 a further milestone report was produced. *The Monaco Declaration* arose from the 2nd international symposium *The Ocean in a High-CO_2 World,* and was approved by 155 scientists from 26 countries with the support of HSH Prince Albert II of Monaco. It calls on policymakers to act quickly to stabilize atmospheric CO_2 at a safe level, not only to avoid dangerous climate change but also to avoid the additional problem of ocean acidification.

EUROPEAN SCIENCE FOUNDATION

Impacts of Ocean Acidification

37

Foreword

www.esf.org

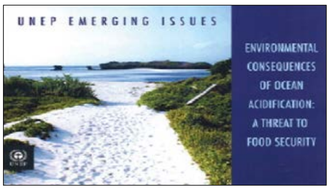
The European Science Foundation Science Policy Briefing on *Impacts of Ocean Acidification* (2009) included recommendations for improved coordination of ocean acidification research and collaboration both at national and international levels, together with integration of efforts between natural and social sciences, in order to understand the impacts on natural resources and humans.

Frequently asked questions about ocean acidification

EPOCA

Introduction

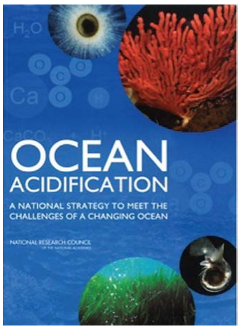
Ocean Acidification Frequently Asked Questions (2010) was published by OCB, EPOCA and UKOA in response to the growing research across disciplines and the increasing need for clear answers by experts to frequently asked questions. In total, 27 experts from 19 institutes and five countries contributed.



UNEP EMERGING ISSUES

ENVIRONMENTAL CONSEQUENCES OF OCEAN ACIDIFICATION: A THREAT TO FOOD SECURITY

Environmental consequence of ocean acidification: a threat to food security. UNEP Emerging Issues Bulletin (2010). With 1 billion people relying on marine protein as their sole protein source, and an expanding global population increasingly reliant on marine food sources including aquaculture, this was the first time ocean acidification was linked to a potential risk to food security.

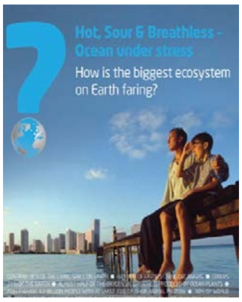


OCEAN ACIDIFICATION

A NATIONAL STRATEGY TO MEET THE CHALLENGES OF A CHANGING OCEAN

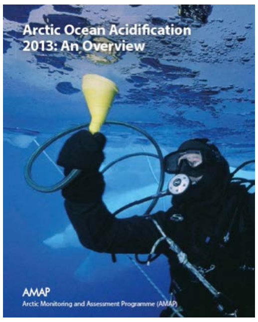
NATIONAL RESEARCH COUNCIL

The National Research Council of the US National Academies Ocean Acidification. A National Strategy to Meet the Challenges of a Changing Ocean (2010). This publication, requested by Congress, is one step amongst many that US scientists and funders have taken towards forming a National Ocean Acidification Research Programme.

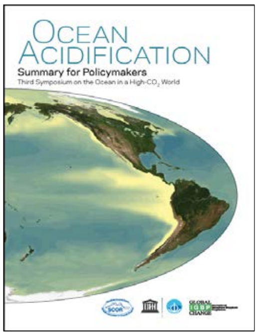


Over the coming decades and centuries, ocean health will become increasingly stressed by at least three interacting factors: rising seawater temperature, ocean acidification and ocean deoxygenation. *Hot, Sour and Breathless: Ocean under stress* (www.oceanunderstress.com) summarizes current knowledge on these three stressors and how they may react together in ocean 'hot spots' of vulnerability. Produced by Plymouth Marine Laboratory in collaboration with leading research programmes and laboratories it has been made available to policy makers at the UNFCCC COPs since 2011 and is available in several languages and regularly updated.

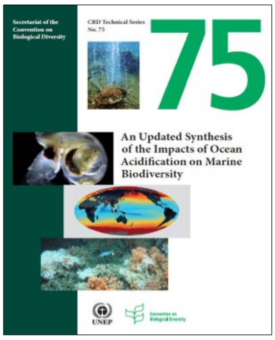
The Intergovernmental Panel on Climate Change's (IPCC) 4th Assessment Report (2007) recognized ocean acidification for the first time in an IPCC report. The 5th Assessment Report (2013-2014) included an in-depth assessment of both ocean climate change and acidification (https://www.ipcc.ch/report/ar5/). The IPCC is currently in its Sixth Assessment cycle and is also undertaking a *Special Report on the Ocean and Cryosphere in a Changing Climate* and another on the *Impacts of Global Warming of 1.5°C*.



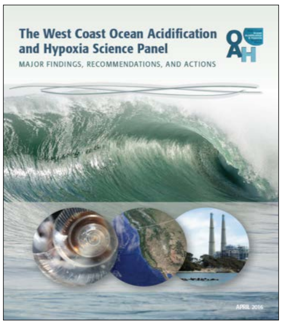
The Arctic Council's Arctic Monitoring and Assessment Programme (AMAP) working group released its *Arctic Ocean Acidification Report* in 2013 (http://www.amap.no/documents/doc/Arctic-Ocean-Acidification-2013-An-Overview/1061). The report introduces the issue of ocean acidification intensification in the cold Arctic waters and presents the results of AMAP's assessment for a general audience. There is also a full report and videos (https://vimeo.com/65512340).



The series of international symposia *The Ocean in a High-CO_2 World* has produced excellent and wonderfully illustrated summaries for policy makers. The latest, *Ocean Acidification Summary for Policy Makers*, produced in 2013, summarises new research findings presented at the 3rd Symposium held in 2012 and is available in English, French, German and Spanish.

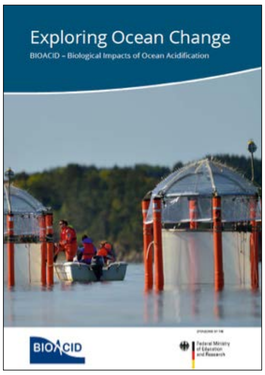


The Convention on Biological Diversity (CBD) published a synthesis report on *Impacts of ocean acidification on marine biodiversity* in 2009. In 2014 CBD published *An updated synthesis of the impacts of ocean acidification on marine biodiversity* (https://www.cbd.int/doc/publications/cbd-ts-75-en.pdf). It presents complex scientific information on ocean acidification in a clear and understandable way, provides an important reference point for scientists, policymakers and anyone else interested in understanding how ocean acidification affects our ocean, its biodiversity and the vital services it provides.



Published in 2016 the *West Coast Ocean Acidification and Hypoxia Science Panel Report* (www.westcoastOAH.org), is a collaboration between ocean management counterparts in California, Oregon, Washington, and British Columbia. OA and hypoxia refer to distinct phenomena that trigger a wide range of marine ecosystem impacts. The Panel considered them together because they frequently co-occur and present a collective West Coast challenge. In particular, OA and hypoxia share a common set of drivers – increased atmospheric CO_2 levels and local nutrient and organic carbon inputs.

The Marine Climate Change Impacts Partnership (MCCIP) was created in 2005 to act as a coordinating framework for the UK, providing marine climate change impacts evidence to decision makers. MCCIP report cards provide regular updates on the current state of scientific understanding in a clear and concise manner. The latest 2017 report card (www.mccip.org.uk/arc10 is based on a series of peer-reviewed papers produced by more than 50 authors, as well as drawing on previous report cards. The papers, including one on ocean acidification and this report card are accessible through http://www.mccip.org.uk/media/1760/2017arc_sciencereview_001_oac.pdf

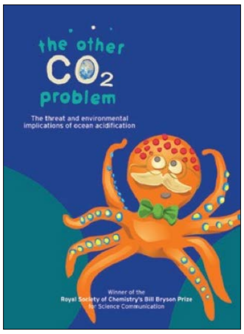


The German research network on ocean acidification BIOACID (Biological Impacts of Ocean Acidification) reached its conclusion in 2017 after eight years of extensive interdisciplinary research with this summary for policy makers: https://www.oceanacidification.de/wp-content/uploads/2017/10/BIOACID_brochure_e_web.pdf

This publication has been developed for the annual climate change negotiations UNFCCC COP23 held in Bonn under the Presidency of Fiji by an international global science partnership, providing evidence-based science for policy making on the impacts of increasing concentrations of carbon dioxide and other greenhouse gases on the ocean and human systems: www.oceansofimpacts.global

Films

In the past decade or so a large number of films have been produced to explain ocean acidification to a wide audience and how the issue is being tackled by scientific studies and new innovative science-policy-outreach partnerships. We select several of them based on their free availability and usefulness to a range of audiences:



A group of 11-15 year old students from Ridgeway School in Plymouth, working with Plymouth Marine Laboratory, have made their concerns about the state of the world's ocean clear through a hard hitting film. *The Other CO$_2$ Problem*, released in 2009, is a 7 minute animation starring characters from King Poseidon's Kingdom beneath the sea and laments the fact that Doctorpus, Britney Star, Michelle Mussel, Derek the Diatom and other subsea creatures are suffering as the ocean becomes more acidic as a result of human activities. The children and their animation won the Royal Society of Chemistry's Bill Bryson Prize for Science Communication. The animation has been translated into French, Spanish, Italian and Catalan (www.oceanunderstress.com).

A powerful short film *Ocean acidification: Connecting science, industry, policy and public*, released in 2011 by Plymouth Marine Laboratory as part of the UK Ocean Acidification Research Programme's outreach. It brings together a wide range of stakeholders concerned about ocean acidification. It has been shown at major events around the world, including the UNFCCC and CBD COPs, World Expo 2012, the East Asian Seas Congress and Rio+20 Earth Summit. Sub-titled versions of this 12 minute film are available in English, Portuguese, Spanish, French and Korean (www.oceanunderstress.com).

Produced in 2012 this video focuses on ocean acidification impacts on oyster hatcheries already occurring along the US west coast and how future US shell fisheries may be impacted (https://www.youtube.com/watch?v=x7Mpl9dZljk).

A fast moving 3 minute cartoon describing ocean acidification by the Alliance for Climate Education in 2014, includes a helpful and fun description of how the chemistry works and impacts marine life and why we should worry (https://www.youtube.com/watch?v=DLg2NMjzh2o).

This 10 minute film, *Testing the Waters: Acidification in the Mediterranean* (https://vimeo.com/101795615) was an output in 2014 from the scientific project MedSeA, funded by the European Community, which studied the impacts of the ocean acidification and warming in the Mediterranean Sea.

Oregon is ground zero for ocean acidification impacts – the water chemistry off its coast is already changing dramatically. For a glimpse into the science, the impacts and the information gaps behind ocean acidification in Oregon, check out this 2016 video where researchers, industry members and policy leaders team up to better comprehend these chemical changes along their coastal waters where ultimately, these changes have the potential to impact everyone that lives there (https://www.youtube.com/watch?v=7h08ok3hFSs).

This 8 minute film released in 2016 by the German research network BIOACID examines the effects of acidification on marine life, from microbes to fish, and biogeochemical cycles in the ocean - and on all those who depend on it (https://www.youtube.com/watch?v=pnp8uQh6VAI).

In this 30 minute 2016 BBC Science documentary Roger Harrabin joins a scientific expedition to the CO$_2$ vents off the remote eastern tip of Papua New Guinea These coral reefs and the CO$_2$ vents are natural laboratories for scientists to study the effects of ocean acidification and offer a worrying glimpse into the future of tropical corals as increasing concentrations of CO^2 in the atmosphere make sea water more acidic. (https://www.youtube.com/watch?v=VCo1wo8gAzQ).

This 5-minute video celebrates the launch of Latin American OCean Acidification Network (LAOCA), in which Latin-American scientists highlight the impacts of ocean acidification on marine resources and ecosystems in the region and the needs for national and international coordination to confront the challenges imposed by this threat (https://youtu.be/Xx3HOqGiXjg)

Further information

Download a copy of this new report on ocean acidification from www.iucn.org/resources/publications.

If you have any further enquiries please contact us at marine@iucn.org.

Sources and contributors

This report draws from:

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We are grateful to all the scientists and experts who contributed to the development of this report, directly but also through the reports listed above. Their contributions have ensured that it represents a broad consensus of the key information and actions needed on ocean acidification.

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