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Ocean acidification - what can we do?

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CAUSES AND CONSEQUENCES OF OCEAN ACIDIFICATION

The oceans have absorbed about one third of anthropogenic carbon dioxide (CO_2) emissions during the past five decades. This massive input of CO_2 generates sweeping changes in the chemistry of seawater, especially on the carbonate system. These changes are collectively referred to as "ocean acidification" because increased CO_2 lowers seawater pH (i.e., increases its acidity).

The basic chemistry of ocean acidification being well understood, future projections are quite straightforward for the surface open ocean for a given atmospheric CO_2 trajectory. Those based on the International Panel on Climate Change (IPCC) scenarios give reductions in average global surface pH of between 0.14 and 0.35 units over the 21st century, which means surface pH may reach 7.8[1] in the year 2100 (Orr, 2011)—compared to 8.18 prior to the industrial era and 8.10 at present. Furthermore, impacts related to ocean acidification will continue to aggravate for centuries even if emissions are stopped (Joos *et al.*, 2011).

1. On the total scale.

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Although the ocean's uptake of atmospheric CO_2 is by far the major driver of ocean acidification globally, two other known or potential causes of ocean acidification have been identified:

- Coastal acidification due to additional pollutants: Nitrogen and phosphate runoff from agricultural, industrial, urban and domestic sources causes acidification of coastal waters. The relative importance of each of these mechanisms—as well as the importance of each relative to that of global CO_2—is a matter of active research, but it seems clear that non-CO_2 inputs can contribute significantly to the overall acidification threat in some coastal regions (Feely *et al.*, 2012).
- Release of methane hydrates into the ocean: Methane hydrates currently stored in the sediments below the ocean represent a significant fraction of the amount of carbon globally stored. Owing to high pressure and cold temperature conditions, methane today remains in stable hydrate form below 300 m. Deep oceanic warming could cause a transition from the hydrate into the gas phase. Microbial aerobic oxidation would then convert methane remaining in the water column, with oxygen, into CO_2, thus contributing to ocean acidification. Due to the thermal inertia of the ocean and the delayed intrusion of heat into the sediments, the process of methane release would be irreversible and would continue for a long time, even after global warming has eventually stopped. However there is no consensus, as of today, as to whether the dissolution of methane hydrates represents a real and significant threat to the oceans in the course of the 21^{st} century.

Consequences of ocean acidification on societies will depend on interactions among and between species and ecosystems (all reacting at different rates and magnitudes), on the interaction of ocean acidification with other ocean stressors; and on responses of each human group affected. Nevertheless, it is clear that the speed and magnitude of acidification is threatening many marine species and ecosystems. Calcifying organisms such as coral reefs, shellfish and zooplankton are among the first potential victims. Therefore ocean acidification will impact various economic sectors (e.g. fisheries, aquaculture, and tourism) and coastal communities, and may also have heavy indirect effects on much broader segments of the world economy and population. It is thus an appropriate time to review the available management and policy options despite the uncertainties surrounding the details of acidification impacts.

OPTIONS TO TAKE ACTION AGAINST OCEAN ACIDIFICATION

Preventing ocean acidification

Given the three potential causes of acidification, this may be done through:

Limiting CO_2 concentration in the atmosphere, either by reducing emissions or by removing CO_2 once emitted. CO_2 and other GHGs have been the primary target of the United Nations Framework Convention on Climate Change (UNFCCC) since its adoption in 1992, and of all subsequent climate talks. International climate negotiations, however, have failed to reach a legally binding, long-term agreement that would include all major and emerging economies to reduce CO_2 and other GHGs emissions so as to meet the target of limiting global average temperature rise to less than 1.5 to 2°C above pre-industrial levels. Regardless, this politically accepted limit chosen "to prevent dangerous anthropogenic interference with the climate system"[2] may not effectively address ocean acidification for two reasons. First, it is still unclear what level of atmospheric CO_2 may constitute a "safe" level with respect to ocean acidification. Second, climate talks deal with cumulative radiative effects and do not prioritize reductions on any one gas (CO_2 instead of others).

Removing CO_2 from the atmosphere once emitted, on the other hand, could also prevent ocean acidification. Of the methods that aim to enhance uptake and storage by terrestrial and oceanic biological systems, or to use engineered (physical, chemical, biochemical) systems, "none has yet been demonstrated to be effective at an affordable cost, with acceptable side effects" (The Royal Society, 2009). Their effectiveness to reduce ocean acidification is technique specific and they hold little promise in terms of the maximum reduction in atmospheric CO_2 they might realistically achieve (Williamson and Turley, 2012). However, calls to evaluate the potential, costs and benefits of geoengineering solutions to ocean acidification grow louder every day.

Reducing local factors of ocean acidification is another lever for mitigating acidification in the coastal ocean[3] (Kelly *et al.*, 2011). The potential for

2. UNFCCC, Article 2.
3. For the open ocean, which is likely to experience the effects of coastal stressors less directly, such policy levers are probably both less important (likely to have less effect) and less feasible (given the governance issues of the high seas).

nutrient controls and other local- and national-scale pollution control measures depends on the relative importance of non-CO_2 inputs in driving ocean acidification, but they could be of critical importance in areas where the chemical effects of terrestrial inputs rival CO_2-driven acidification. Where local and national economies rely heavily upon carbonate-dependent ecosystem services, for example shellfish farming and coral tourism, reducing local acidifying factors could produce results both faster and in a more politically feasible manner than would a global CO_2 solution alone.

Reducing the risks of a potential release of methane hydrates by limiting the greenhouse effect, hence ocean warming, may be done either by reducing emissions of GHGs or by managing solar radiation. To the extent that we really have an acidification problem exacerbated in the long-term by the rise of global temperatures, some non-CO_2 GHG emissions reductions appear technologically feasible and politically viable (e.g., for PFCs, SF_6 or HFCs). However, any such measures would not be sufficient by themselves to significantly limit warming, largely driven by CO_2 during this century. On the other hand, methods for managing solar radiation, and therefore thermal impacts, have gained some attention. However, Williamson and Turley (2012) conclude that their effects on acidification are uncertain in both their magnitude and direction.

Strengthening ecosystem resilience to ocean acidification

In addition to tackling the root causes of ocean acidification, there is an increasing interest in boosting resilience in marine ecosystems to better tolerate its impacts. It is especially important given that acidification is already happening and is expected to continue even if CO_2 emissions are rapidly mitigated. As of 2013, empirical studies examining population or ecosystem resilience to ocean acidification are not available. However, many of the concepts regarding ecosystem resilience to other stressors, including global warming, overfishing, nutrient pollution and habitat alterations, are applicable to ocean acidification.[4] It is likely that these other stressors decrease ecosystem resilience to acidification, and reciprocally, acidification will decrease ecosystem resilience to these other stressors. Therefore the tools commonly used to increase resilience and alleviate the pressure from various stressors are also of primary importance for ocean acidification. This includes but is not limited to well-connected and representative networks of marine protected areas.

The evidence for human-mediated increases in resilience is sparse, and building resilience is not a solution to ocean acidification *per se*. Ultimately, increasing resilience will only be effective as a harm-mitigation technique if it is accompanied by a strong limitation of CO_2 concentration in the atmosphere.

Adapting human activities in anticipation of or reaction to ocean acidification

Adaptation to ocean acidification covers a wide range of potential actions taken by individuals or human groups, and such measures will inevitably be necessary given the inertia of past CO_2 emissions' effect on present and future ocean acidification.

Practical examples are still scarce, but revenue-generating activities like fisheries or aquaculture will have opportunities to adapt to an acidified ocean as the knowledge base improves and impacts become more noticeable. The potential of adaptation is likely to be high for certain specific activities and issues within a narrow range of pH variation—for example, in commercial shellfish operations—but limits will be met when entire ecosystems and life cycles are disrupted beyond a critical threshold.[5] Relocation of activities will hence complement local adaptation strategies.

Repairing damages when the ocean has already acidified

Acidity may be reduced **using additives other than iron.** The addition of powdered alkaline rocks such as calcium carbonate ("liming"), has been used to counteract lake acidification for many years (Weatherley 1988). Similar ocean-based techniques aim at accelerating the natural process of rock weathering that supplies alkaline substances through rivers and run-off.

There is limited experimental evidence that alkalinisation could be useful in coastal environments such as mud flats (Green *et al.*, 2009). Chemical buffering seems unlikely to scale up, however. Global models suggest that ocean alkalinisation has the potential to mitigate atmospheric CO_2 and ocean acidification but requires large-scale, long-term, "alkalinity intensive" additions. Much work

4. For example, ecosystems with higher diversity are expected to be more resilient to environmental stress (Folke *et al.*, 2004).

5. Hoegh-Guldberg *et al.* (2007) for instance find that consequences on coral reefs become unmanageable for $[CO_2]_{atm}$ above 500 ppm.

remains to be done on the biogeochemical and ecological impacts of the chemical additions, costing, as well as on the development of methods for verification and monitoring.

Another potential response to the threat of ocean acidification is to use opportunities for **ecological restoration**, going beyond the current focus on restoring species, populations or habitat condition, to approaches that anticipate future acidification. Estuaries provide such an opportunity as they are local hot spots of acidification in which substantial economies are reliant on healthy functioning ecosystems. They have been acidifying for decades due to nutrient enrichment, changes in river flows with greater freshwater input reducing buffering rates, and inputs of other "acidifying" chemicals from the air and run-off, such as nitrogen and sulphur. Shellfish industries are already experiencing increased mortality of larval and juvenile oysters in estuaries (Green *et al.*, 2009), which has forged new collaborations between scientists, conservation groups and industry. Ecological restoration projects now employ strategies of placing cultch (shell material) to speed up recovery of previously depleted shellfish beds (Beck *et al.*, 2009).

WEIGHING POTENTIAL ACTIONS AGAINST OCEAN ACIDIFICATION

Not all options presented here are equally effective or feasible. They also interact and therefore need to be considered as a bundle. For instance: building ecosystem resilience will be all the more efficient as acidification is limited; locally reducing acidity could become a regular management measure for marine protected areas; local action against coastal acidification could stimulate more ambitious efforts on CO_2; having techniques available to manage solar radiation may be a disincentive to cut GHG emissions, including CO_2.

Any of the alternatives discussed here merely buys time to reduce CO_2 emissions, which remains vital whatever other action is taken. The first key question is therefore whether and how ocean acidification can make a difference in the complex and difficult UNFCCC talks. Incorporating ocean acidification into the negotiations would aim both at encouraging drastic CO_2 emissions reductions and at ensuring that mitigation policies take non-thermal effects of CO_2 into account—hence differentiating CO_2 from other GHGs. We can speculate that ocean acidification might be able to provide additional urgency to act, as the chemical understanding is clear and impacts are very likely irreversible on a human time scale. At the same time, the possible disappearance of some island States, more extreme climate events in densely populated deltas and low-lying coastal areas, or the drive of hundreds million people towards food insecurity because of desertification, have so far been insufficient arguments for the international community to take appropriate coordinated action on GHG emissions. There are therefore few reasons to be optimistic that ocean acidification will fare better as an argument.

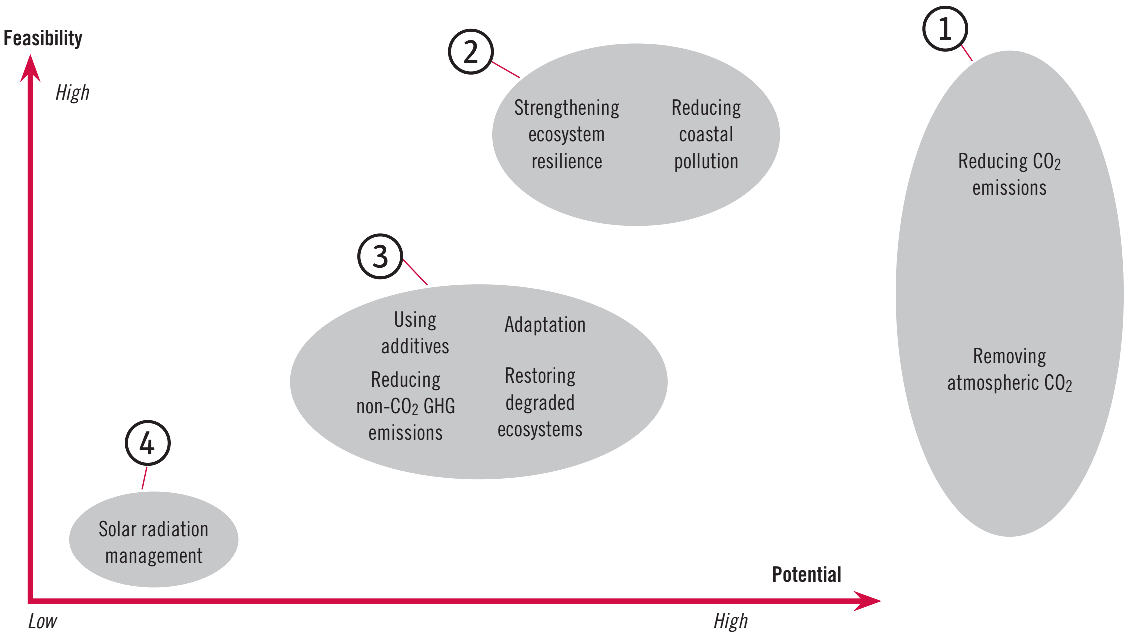
No geoengineering method seems to provide an easy or readily acceptable alternative solution to ocean acidification, in contrast to low-carbon technologies (Joos *et al.*, 2011). However, methods to remove CO_2 from the atmosphere may become a necessity in light of the present trajectory of CO_2 emissions. They involve fewer uncertainties and risks than solar radiation management techniques, and are much more effective against acidification. In the same vein, reducing non-CO_2 GHG emissions will not make a big difference in the short to medium term as far as global acidification is concerned, but it may prove opportune in the long term to prevent release of methane hydrates and acidification in specific areas.

Reducing coastal pollution sources is important for many reasons other than acidification. However—and probably more efficiently than in the case of the global climate talks—acidification can stimulate more effective and ambitious action towards local pollution reduction. It can help build new strategic alliances with powerful stakeholders like the fisheries and shellfish industries. To this end, a spatially explicit evaluation of the relative importance of different causes of acidification is necessary to maximize the utility of smaller-scale policy recommendations.

Strengthening ecosystems resilience and restoring the ones that have suffered from ocean acidification should be another cornerstone of action. The benefits of such action are manifold: these techniques address many stressors simultaneously; much can be done within single jurisdictions, thus minimizing transaction costs; and many years of research have generated extensive experience in conservation and restoration. In addition, it appears that easy and low-tech actions like returning crushed shell material to coastal habitats can in some cases substantially increase pH and mitigate localized acidification impacts.

In an attempt to synthesize the discussion, Figure 1 qualitatively compares the various options discussed. "Potential" refers to how effective each option may be with regard to fighting ocean acidification, and "feasibility" is understood as reflecting the ratio between the technological, political, and economic opportunities and barriers. This diagram is intended to be heuristic, rather than a

Figure 1. Comparing potential and feasibility of management options



formal accounting; what is important is the relative position of options along the two axes. Four clusters arise:

- 1. The two options targeting CO_2 concentration in the atmosphere clearly have the greatest potential, and cannot be compared with others—at least not on the same scale. The political and social feasibility of immediate reductions in CO_2 emissions raises concerns while technology is largely available: depending on the viewpoint, feasibility can hence be considered relatively low or high. CO_2 removal may be politically easier but there are high uncertainties regarding technologies as no large-scale demonstration has been undertaken.
- 2. Strengthening ecosystem resilience and reducing coastal pollution have both high potential and feasibility. They are no-regret strategies (i.e. justified under all plausible future scenarios) and offer massive co-benefits: they are probably the two options offering the greatest combination of political and biochemical advantage as of today.
- 3. Then comes a cluster of four options (adapting, restoring degraded ecosystems, using additives, reducing non-CO_2 GHG emissions) that have a lower potential than clusters 1 and 2, and rank somewhere in the middle in terms of feasibility. They still deserve significant attention either because they are effective in the short term or because they have important co-benefits. Their respective potential and feasibility cannot be compared with the current state of knowledge.
- 4. Last, solar radiation management appears to be of little potential with respect to counteracting ocean acidification in the short-to-medium term, although reducing warming *via* radiation management may be more relevant at time scales of a few centuries, depending on the projected risk of methane hydrate dissolution.

LEGAL AND POLITICAL BASIS FOR ACTION

The review of options to combat ocean acidification raises the question of whether new legal instruments (multilateral environmental agreements such as conventions and protocols, or domestic statutes) are needed, or whether the legal basis for action already exists while policies (i.e. implementation efforts) are the limit. The answer appears to be the latter: although it is a recently emerged global environmental concern, ocean acidification does not require significant changes in existing legal frameworks. Reducing CO_2 and other GHG emissions, reducing local nutrient pollutions, protecting and restoring ecosystems, adapting human activities, or introducing additives: the frameworks to take action are already in place to a large extent at the global, regional, national and local levels. What is lacking is implementation.

At the global level, GHG emissions are handled under the UNFCCC, and as Harrould-Kolieb and Herr (2011) affirm, "although the UNFCCC was not originally designed to address ocean acidification, it does provide one framework within which both ocean acidification and climate change can be tackled. Setting up a second international mechanism to deal solely with CO_2 reductions would be superfluous, confusing and unrealistic". However, many domestic policies have, so far, failed to match the Convention's objectives.

Besides the UNFCCC, CO_2 uptake by the ocean easily fits the definition of a "pollution of the marine environment" under Article 1 of the United Nations Convention on the Law of the Sea (UNCLOS): "the introduction by man, directly or indirectly, of substances or energy into the marine environment, including estuaries, which results or is likely to result in such deleterious effects as harm to living resources and marine life, hazards to human health, hindrance to marine activities, including fishing and other legitimate uses of the sea, impairment of quality for use of sea water and reduction of amenities". The 10th Conference of the Parties to the Convention on Biological Diversity (CBD's COP 10, Nagoya, Japan) made ample reference to ocean acidification, and several of the 2020 Aichi targets adopted under its new Strategic Plan are also relevant to acidification.[6] Whether these crucial objectives will be met is, again, a matter of designing and implementing appropriate policies at the domestic level.

As of today, one important global regulatory gap that may hamper responses to ocean acidification is the absence of a clear legal framework to establish marine protected areas in areas beyond national jurisdiction. As to regulating CO_2 removal methods, the international legal framework seems sufficient for most techniques[7] but will have to be strengthened for others as they become operational. Ocean alkalinisation would fall under the scope of the 1996 Protocol to the London Convention on the prevention of marine pollution by dumping of wastes and other matter, but further discussions will be needed on the various additives, the applicable regime under the Protocol and their potential environmental impacts—whether positive or negative. Solar radiation management is not covered by any international governance framework, but it remains marginal in the ocean acidification debate.

The regional level has seen the development of many legal instruments and policies to fight land-based pollutions over the past decades. Many of these efforts used the impetus of the 1992 Earth Summit, the 1995 Global Programme of Action for the Protection of the Marine Environment from Land-based Activities and the 2002 Johannesburg Plan of Implementation which called States to "make every effort to achieve substantial progress (…) to protect the marine environment from land-based activities". For example, the European Union adopted the Water Framework Directive (2000) and the EU Marine Strategy Framework Directive (2008), and specific protocols were adopted within several UNEP regional seas frameworks. Yet such protocols have not received the political attention they deserve.

At the national level, a systematic review is out of reach but we can illustrate a number of applicable legal instruments with the U.S. example. The U.S., who ratified the UNFCCC but are not Party to the UNCLOS and CBD, are relatively well equipped to contribute to combat acidification. Kelly and Caldwell (2012) relate that "the United States government has begun to take notice of the acidifying ocean in small but important ways. In 2009, Congress passed legislation focused squarely on ocean acidification,[8] establishing a federal interagency

6. Such as those on pollution, including excess nutrient, or on ecosystem restoration.

7. Ocean iron fertilization e.g. is regulated by a resolution (LC-LP.1 (2008)) adopted under the London Convention and Protocol in which Contracting Parties declared that given the present state of knowledge, ocean fertilization activities other than legitimate scientific research should not be allowed.

8. On March 30, 2009, President Obama signed the Federal Ocean Acidification Research and Monitoring (FOARAM) Act, 33 U.S.C. § 3701 et seq. (authorizing funding, developing interagency plan on ocean acidification, and establishing an acidification program within the National Oceanographic and Atmospheric Administration).

working group on the issue, and a research programme within the National Oceanographic and Atmospheric Administration. An ocean acidification task force consisting of a collection of independent scientists and policymakers was convened to provide advice to the interagency working group". Legally, the U.S. Clean Water Act regulates marine pH, and the Clean Air Act allows the U.S. to regulate CO_2 as a pollutant.

Finally, at the local and subnational levels, still with the U.S. example, Kelly and Caldwell (2012) highlight the legal authority of state and local jurisdictions to control coastal pollutants that may make those habitats more vulnerable to acidification.

A fundamental characteristic of the ocean acidification issue is therefore the current discrepancy between essentially appropriate legal frameworks at all scales, and insufficient or inefficient policies to translate them into action.

A STRONG ARGUMENT TO SUCCEED WHERE WE FAILED

Reviewing available options should not obscure a number of handicaps that will undoubtedly hamper action against ocean acidification. Three of these handicaps stem from the nature of impacts: (i) these impacts are still poorly defined and hardly quantified; (ii) they are largely "invisible", both because they are difficult to isolate from those of other stressors, and because they occur underwater (unlike the effects of acid rain on forests, for example); (iii) ocean acidification is a global issue (i.e. it is happening in the entire ocean and needs to be addressed globally) but will impact societies and ecosystems very unevenly and with different time scales. Hence motivation to take action will be uneven as well. Another handicap of a different nature is that most options reviewed here have already been identified in the context of other environmental problems; one must admit that we have not been very successful in implementing them with adequate intensity at the appropriate scale—beyond the many circumscribed success stories.

These are all reasons why one should not expect an easy solution to ocean acidification. The foregoing discussion means we have to succeed where we have failed to a large extent so far: reducing CO_2 emissions, protecting marine ecosystems from various stressors, restoring the ones that have been degraded, and developing last-resort technologies to cope in the worst-case scenario. Given the uncertain future outcome of CO_2 emissions reductions efforts, any action that can be taken will have to be, however marginal its effect may seem—especially the actions which have important subsidiary environmental benefits. In any case, ocean acidification is one more reason why climate change talks must succeed. Admittedly it is one in an already long list, but it also has aspects (rapid time scales, economic and social impacts, potential irreversibility) that may help make a difference in the larger push to control our ever-rising CO_2 emissions.

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