

OCB-OA: Management and mitigation options

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What are the options for mitigating the effects of elevated CO₂ on marine life?

Basic: Thus far the primary OA management and mitigation actions proposed have focused on 1) reducing anthropogenic CO₂ emissions and hence stabilizing air and ocean CO₂ concentrations, and 2) maximizing biotic resilience and adaptation to elevated CO₂ using conventional marine management practices (MPAs, pollution and overfishing reduction, etc.). However, stabilization of atmospheric CO₂ below harmful levels may not be achieved, and conventional, passive management practices may not be effective against CO₂ impacts. Some alternative physical, biological, chemical, and hybrid conservation methods have been proposed, but research into their potential effectiveness, cost, safety, and scale of application has yet to be seriously undertaken. A broader and deeper search for and evaluation of new marine conservation practices is needed in the increasingly likely event that unsafe CO₂ and pH thresholds are surpassed.

Would adding antacids to the ocean be helpful?

Basic: Acids can be neutralized with chemical bases. A variety of schemes have been proposed wherein seawater CO₂ acidity could be neutralized through the addition of base carbonate or silicate minerals or their derivatives. While such chemical methods are commonly used in saltwater aquaria to maintain coral and shellfish health, the potential safety and cost effectiveness of these approaches in addressing local to global OA have yet to be fully researched.

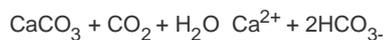
Intermediate/Technical: Chemical bases are effective absorbers of CO₂ and carbonic acid. Indeed, CO₂ reactions with carbonate and silicate base minerals are the primary ways Nature naturally consumes excess atmospheric CO₂ and ocean acidity over geologic time scales (Archer et al. 2009). Methods that accelerate these natural reactions are therefore pertinent to CO₂ and OA mitigation. Prior to concerns over OA, Kheshgi (1995) proposed large-scale ocean addition of a base, calcined limestone (Ca(OH)₂), to accelerate the removal of CO₂ from the atmosphere. It was later proposed that limestone be directly added to carbonate-undersaturated depths in the ocean to increase alkalinity, effecting both carbonic acid neutralization and increased CO₂ uptake (Harvey 2008). For the same purpose, coastal addition of finely ground silicate minerals has been suggested (Schuiling and de Boer 2011). The local amendment of waste shell material (CaCO₃) to benthic sites has been shown to produce seawater water chemistry beneficial for the recruitment of calcifying marine bivalves (Green et al. 2012).

Land-based point-source or atmospheric CO₂ mitigation schemes using base minerals can generate alkaline solutions that, in addition to consuming CO₂, could be helpful in combating OA (House et al 2007; Rau 2008; Rau 2011). Here, waste or air CO₂ is converted to dissolved alkaline bicarbonate, which when added to the ocean would help stabilize if not increase buffering capacity and calcium carbonate saturation state. The common use of CO₂/calcium carbonate alkalinity generators to maintain pH and carbonate saturation state for corals and shellfish in saltwater aquaria (Huntington 2002) illustrates, on a small scale, the potential benefit of such an approach to combating local/regional OA. However, further research on the possible scale, safety, and cost-effectiveness of the preceding OA management/mitigation methods is needed (Rau et al. 2012). —G. Rau

If we increase shellfish aquaculture, will the shells help remove carbon dioxide?

Basic: Creating the minerals that make up shellfish shells actually produces more CO₂. Growing more shellfish won't chemically offset ocean acidification. Aquaculture of shellfish will help overcome decreases in wild shellfish populations that OA might cause, though.

Intermediate/Technical: A common misconception in biogeochemistry is that formation of calcite removes carbon dioxide (Zeebe and Wolf-Gladrow 2001). As can be clearly seen in the reverse of the following equation the formation of calcite actually produces CO₂:



The calcification process does take up bicarbonate ion, but it causes shifts in the carbon system in seawater that result in a lower pH and an increase in pCO_2 . Many organisms convert bicarbonate to the carbonate they use to build their shells, and this produces hydrogen ions, thus increasing acidification. Most coral reefs, for example, on the time scales we are interested in, are small sources of CO_2 to the atmosphere rather than sinks. From an ecosystems point of view, even well-intended aquaculture could cause unintentional harm by altering coastal landscapes, increasing pollution and disease, or releasing genetically altered or foreign species into the environment. Any activity aimed at reducing ocean acidification should be considered in a wider context to avoid replacing one environmental impact with another. —A. Cohen, S. Widdicombe, C. Turley, R. Feely

Will CO_2 uptake by marine plants help stop climate change and ocean acidification?

Basic: On land, forests are important for taking up CO_2 from the atmosphere. In the ocean, marshes, mangroves, and seagrass meadows take up CO_2 from seawater. These marine environments can store a large amount of carbon and may help offset ocean acidification locally.

Intermediate: Carbon stored in coastal environments like mangroves and seagrass meadows is called “blue carbon”. Like organic carbon on land stored in trees, this “blue carbon” is locked into organic matter that can be preserved for decades or longer. Research is continuing on how large these environments are, and how much carbon they can store. It appears that these areas are natural hot spots for carbon sequestration. Moreover, seagrass beds often occur near coral reefs. Blue carbon may represent a way of offsetting some amount of ocean acidification locally. Future conservation efforts may target these environments to make the most of their ability to sequester carbon. (See also the *OA and Photosynthesis* section.) —C. Turley, D. Herr, C. Duarte

Advanced: The protection of organic carbon stored on land, especially in forests, is considered to be an important method for mitigating climate change. United Nations collaborative initiative on Reduced Emissions from Deforestation and Degradation (REDD+) in developing countries maintains terrestrial organic carbon (C_{org}) stores through financial incentives for forest conservation, which requires rigorous monitoring of C_{org} stores and emissions (IPCC 2003 and 2007).

There are similar initiatives to protect ‘blue carbon’ stores in coastal ecosystems such as tidal salt marshes, mangroves and seagrass meadows which are some of the most productive ecosystems on Earth and also store large amounts of organic carbon. Unlike terrestrial forests, where the C_{org} stores are dominated by the living trees, the C_{org} stores of coastal vegetated habitats are dominated by the C stored in their organic-rich soils. Research into these ‘blue carbon’ stores are less advanced than for terrestrial systems (Duarte et al. 2011) but C stores of mangroves and seagrass meadows have been estimated at $1,023 \text{ MgC ha}^{-1}$ (Donato et al. 2011) and $139.7 \text{ MgC ha}^{-1}$, (Fourqurean et al. 2012), respectively, and the carbon burial in seagrass meadows is between 48 and 112 Tg yr^{-1} , showing that they are natural hot spots for carbon sequestration (Kennedy et al 2010).

Productive seagrass beds are often located near coral reefs e.g. Florida Reef Tract. Recent work has shown that calcification of calcareous macroalgae can be stimulated by CO_2 uptake of seagrasses (Semesi et al. 2009) and photosynthetic CO_2 uptake associated with seagrass beds may create a local ocean acidification refugia, through local controls of carbonate chemistry (Manzello et al. 2012). Additionally, seagrass productivity is expected to be stimulated with future ocean acidification (Beer and Kock 1996, Jiang, et al. 2010), which could represent a potential positive feedback to their ability to serve as ocean acidification refugia (Palacios and Zimmerman, 2007). Other calcifying organisms may also benefit as seagrasses are not limited to the tropics so they have the potential to locally buffer ocean acidification within other coastal ecosystems.

Conservation of vegetated coastal habitats may help protect coastal CO_2 sinks and, thereby, help mitigate climate change and provide refugia from ocean acidification to calcifiers locally. Whereas vegetated coastal habitats have the potential to provide effective refugia from ocean acidification, their role in stopping climate change is likely to be modest at best, and they will not stop but only locally buffer ocean acidification. —C. Turley, D. Herr, C. Duarte

Can geoengineering solutions for climate change also help OA?

Basic: Most geoengineering proposals try to limit the effects of climate change without tackling its cause: atmospheric carbon dioxide. So geoengineering proposals that seek to cool the planet will not address OA. On the other hand, proposals that capture carbon dioxide and store it away from seawater will mitigate the effects of OA somewhat. Most such proposals are only cost- or energy-effective on very small scales.

Intermediate: Most proposed geoengineering approaches to limit climate change attempt to provide symptomatic relief from climate change without addressing the root cause of the problem — excess carbon dioxide in the environment. Most geoengineering proposals

address the climate consequences of our carbon dioxide emissions but do not address the chemical consequences of these emissions. For example, strategies that seek to cool the Earth by reflecting additional sunlight to space would have little direct effect on ocean chemistry and therefore would not significantly diminish ocean acidification.

Some proposals have sought to diminish changes in ocean chemistry by adding compounds to the ocean that would chemically neutralize acids. However, reversing ocean acidification this way would require adding an amount of material much larger than the amount of carbon dioxide we are emitting to the atmosphere. Therefore, these proposed solutions would require a new mining and chemical processing infrastructure as large as our current energy system. It has been suggested that buffering the global ocean with calcium carbonate would require an annual application of at least 30 times as much limestone as is mined by humans today (largely for cement production), and this would have to be somehow distributed more or less evenly across all of the ocean basins. It seems reasonable to suggest that this level of effort and spending would be better applied to transforming our energy system away from dependence on a finite pool of fossil fuel resources to use of renewable, infinite resources— which would also prevent carbon dioxide from entering the environment in the first place instead of requiring us to consider neutralizing its effects after it is already spreading through the atmosphere and oceans. —K .Caldeira, C. Turley, D. Hutchins

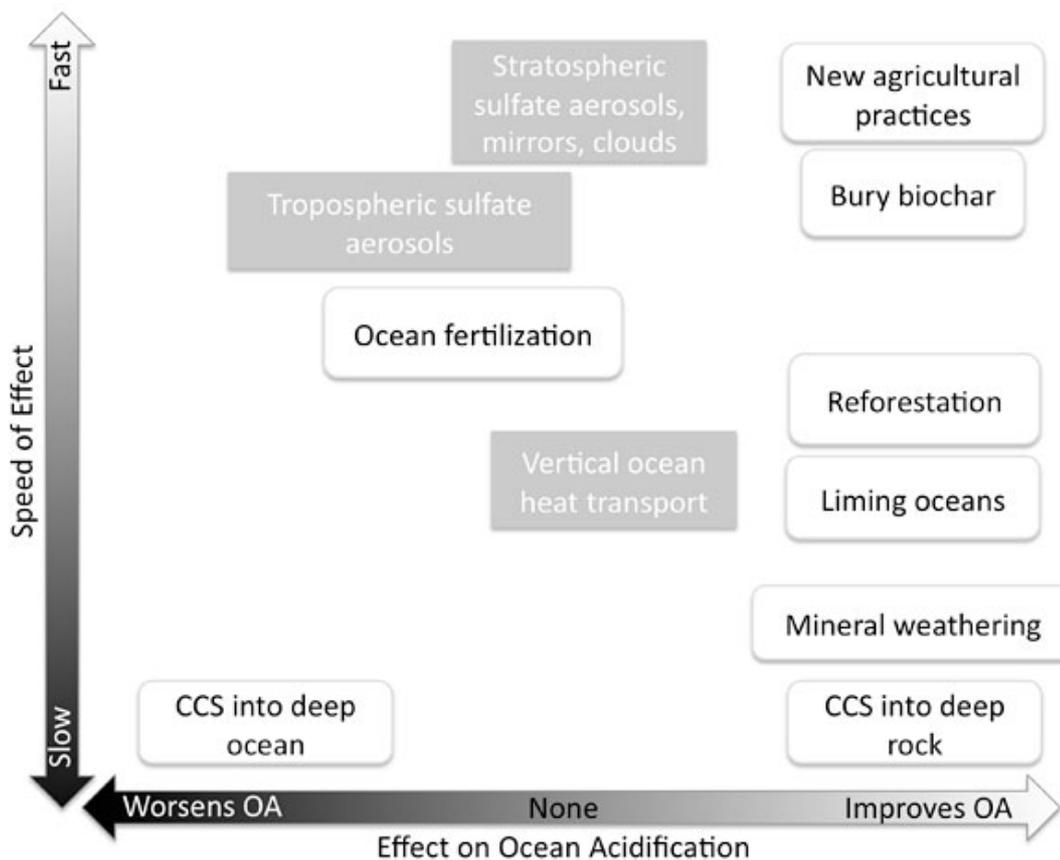
Advanced: Geoengineering is the deliberate large-scale manipulation of the planetary environment to counteract anthropogenic climate change. Many proposed geoengineering approaches to limit climate change attempt to provide symptomatic relief from climate change without necessarily addressing the root cause of the problem — excess carbon dioxide in the environment.

Generally, geoengineering techniques can be divided into solar radiation management (SRM) and carbon dioxide removal (CDR) (Royal Society 2009). Many geoengineering proposals such as the SRM techniques address the climate consequences of our carbon dioxide emissions but do not address the chemical consequences of these emissions. For example, strategies that seek to cool the Earth by reflecting additional sunlight to space would have little direct effect on ocean chemistry and therefore would not significantly diminish ocean acidification.

The future magnitude of ocean acidification will be very closely linked to atmospheric CO₂; it will, therefore, depend on the success of emission reduction, and could also be constrained by geoengineering based on most CDR techniques (Joos et al. 2011). However, some ocean-based CDR approaches would (if deployed on a climatically significant scale) re-locate acidification from the upper ocean to the seafloor or elsewhere in the ocean interior (Williamson and Turley 2012). If solar radiation management were to be the main policy response to counteract global warming, ocean acidification would continue to be driven by increases in atmospheric CO₂, although with additional temperature-related effects on CO₂ and CaCO₃ solubility and terrestrial carbon sequestration.

It seems reasonable to suggest that this level of effort and spending would be better applied to transforming our energy system away from dependence on a finite pool of fossil fuel resources to use of renewable, infinite resources— which would also prevent carbon dioxide from entering the environment in the first place instead of requiring us to consider neutralizing its effects after it is already spreading through the atmosphere and oceans. Strong and rapid mitigation measures, to stabilize atmospheric CO₂ at near-current levels, would therefore provide the policy action most likely to limit ocean acidification and its associated impacts.—K .Caldeira, C. Turley

Figure 7: Geoengineering and ocean acidification. Geoengineering measures that have been suggested to deal with climate change, their effect on ocean acidification, and their timetable for acting. Open boxes indicate strategies considered as “remediations,” or those that attempt to remove the causes of climate change, and gray boxes indicate “interventions,” or those that attempt to moderate the results of climate change. CCS stands for carbon capture and sequestration. From Cooley and Mathis, in revision, *Ocean Yearbook*.



What can we do about ocean acidification on local and regional scales?

Basic: Reducing local pollution might offset some of the local changes caused by ocean acidification. This could increase the overall health of marine ecosystems. But this would buy only a little time, because the root cause of ocean acidification is global atmospheric CO₂ emissions.

Intermediate: In areas with high levels of local pollution into a restricted environment (e.g., bays and estuaries), mitigation of these local sources of pollution may be able to help offset some of the local pH change caused by ocean acidification. However, local-scale mitigating or remediating action is likely to have only local-scale effects, and would only be relevant in locations in which non-CO₂ pollution exacerbates global CO₂-driven acidification. These small-scale actions are concrete steps that jurisdictions can take and may provide important local benefits (see, e.g., Green et al. 2009; Waldbusser et al. 2011), and in particular may serve to increase the resilience of coastal ecosystems in the context of multiple stressors to these environments (see, e.g., Crain et al. 2008). But ultimately any local-scale effort to control ocean acidification's effects probably buys only a small amount of time as national governments and international consortia struggle to control global CO₂. Because unilateral action by a small jurisdiction to address the root cause of ocean acidification (i.e., CO₂ emissions) would not substantially mitigate the problem at the scale of the jurisdiction, emissions reduction at the global scale remains the central policy goal for addressing ocean acidification. —K. Caldeira, R. Kelly, C. Turley

Will capping atmospheric CO₂ at 350 or 400 ppm stop OA?

Basic: No. Atmospheric CO₂ is already at 390 ppm. If we could return to 350-400 ppm, ocean chemistry would return to present day levels, but these may already be harming some organisms. Even if we stabilized emissions to hold atmospheric CO₂ steady, some of this CO₂ will continue to enter the deep ocean for centuries and affect deep water communities.

Intermediate: Atmospheric CO₂ is already at 390 ppm and is increasing at about 2 ppm per year. Without dramatic reductions in CO₂ emissions, atmospheric CO₂ will continue to rise, and most emission forecasts for the near future indicate a likely increase (rather than decrease) in atmospheric CO₂ growth rate. The first step in addressing ocean acidification, therefore, is to stabilize and eventually reduce CO₂ emissions. Atmospheric CO₂ almost certainly will peak well above 400 ppm, because we will not stop increasing emissions in the next 5 years. The impacts on marine life at the peak CO₂ level may be substantial. In the long run, it may be possible to reduce atmospheric CO₂ through natural and artificial uptake mechanisms. The chemistry of seawater is reversible, and returning to 350-400

ppm would return pH and carbonate saturation levels to approximately their current conditions. However, some research has suggested that even current-day conditions may be deleterious for some organisms, and it is even less clear if future biological impacts due to peak CO₂ will be reversible. Even if we stabilized CO₂ emissions, atmospheric fossil fuel CO₂ will continue to penetrate into the deep ocean for the next several centuries, which may impact deep water organisms such as cold-water corals. — S. Doney

Last updated: September 24, 2012

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