

## **Addressing ocean acidification as part of sustainable ocean development**

Submitted to Ocean Yearbook on Friday, July 13, 2012

Accepted October 9, 2012

### **Abstract**

Many of the declarations and outcome documents from prior United Nations international meetings address ocean issues such as fishing, pollution, and climate change, but they do not address ocean acidification. This progressive alteration of seawater chemistry caused by uptake of atmospheric carbon dioxide (CO<sub>2</sub>) is an emerging issue of concern that has potential consequences for marine ecosystems and the humans that depend on them. Addressing ocean acidification will require mitigation of global CO<sub>2</sub> emissions at the international level accompanied by regional marine resource use adaptations that reduce the integrated pressure on marine ecosystems while the global community works towards implementing permanent CO<sub>2</sub> emissions reductions. Addressing ocean acidification head-on is necessary because it poses a direct challenge to sustainable development targets such as the Millennium Development Goals, and it cannot be addressed adequately with accords or geoengineering plans that do not specifically decrease atmospheric carbon dioxide levels. Here, we will briefly review the current state of ocean acidification knowledge and identify several mitigation and adaptation strategies that should be considered along with reductions in CO<sub>2</sub> emissions to reduce the near-term impacts of ocean acidification. Our goal is to present potential options while identifying some of their inherent weaknesses to inform decisionmaking discussions, rather than to recommend adoption of specific policies. While the reduction of CO<sub>2</sub> emissions should be the number one goal of the international community, it is unlikely that the widespread changes and infrastructure redevelopment necessary to accomplish this will be achieved soon, before ocean acidification's short-term impacts become significant. Therefore, a multi-faceted approach must be employed to address this growing problem.

## **1. Introduction**

Global economic growth and human development in the Anthropocene Era have caused widespread environmental degradation, but in recent decades, awareness has grown that future human survival depends on carefully managing Earth's resources. In the 1980s, the United Nations established the World Commission on Environment and Development (WCED) to address how to balance these considerations. Such "sustainable development", as defined by the WCED, "meets the needs of the present without compromising the ability of future generations to meet their needs" (World Commission on Environment and Development 1987, 15). Applying this temporally equitable perspective requires first assessing short- and long-term outcomes of past growth, development, and policy decisions at local to global scales. Oceanic studies show that human development to date has altered the marine environment via waste emission, marine resource extraction, freshwater diversion, and other activities as much as many major planetary processes have. Sustainable development in the future therefore requires humans to pay attention to both the mechanisms of environmental impacts and how well we address those impacts with current measures.

Major United Nations international meetings since the WCED's establishment have sought to make sustainable development understandable and achievable. The Rio Declaration from the 1992 United Nations Conference on Environment and Development (UNCED) underscores how equity underlies sustainable development, given humans' total dependence on limited natural resources (United Nations Conference on the Human Environment 1972). UNCED outcome documents, including Agenda 21, the Forest Principles, the Convention for Biological Diversity (CBD; United Nations 1992a), and the United Nations Framework Convention on Climate Change (UNFCCC; United Nations 1992b) outline concrete goals in a range of topical areas that will promote sustainable development. The Johannesburg Declaration from the 2002 World Summit on Sustainable Development (WSSD; United Nations 2002a) reaffirms international commitment to sustainable development and emphasizes multilateralism to tackle specific problems strongly aligned with the Millennium Development Goals, including chronic hunger, armed conflict, natural disasters, and disease.

Many of the declarations and outcome documents from UNCED and WSSD address ocean issues such as fishing, pollution, and climate change. However, these documents do not address ocean acidification (OA), the progressive alteration of seawater chemistry caused by uptake of atmospheric carbon dioxide<sup>1</sup>, primarily because it is an emerging issue of concern. As a global process driven by anthropogenic carbon dioxide emissions that has varying local effects, OA has many characteristics in common with climate change. UNFCCC addresses carbon dioxide emissions in the context of greenhouse gas emissions and their interaction with the Earth's climate. However, only a specific subset of the mitigation or geoengineering options discussed in UNFCCC can be considered because OA only responds to methods that alter atmospheric or oceanic CO<sub>2</sub> concentrations. Like climate change, addressing OA will require both mitigation of global CO<sub>2</sub> emissions and regional marine resource use adaptations that reduce the integrated pressure on marine ecosystems. This nested approach is necessary because different timescales are required to implement CO<sub>2</sub> mitigation and OA- or climate change-targeting adaptations. Achieving significant reductions in CO<sub>2</sub> emissions depends on developing international policy that influences global economic and social development, which is a challenging and long-term goal that could take decades. However, some of the impacts of ocean acidification are already apparent, which underscores the need to take immediate action and take adaptive measures to maintain marine resources. In this chapter, we review the state of knowledge about OA, discuss forecasts, mitigation, and adaptation strategies, and consider how OA relates to sustainable development goals and mechanisms. We conclude by reviewing some of the first steps that are available to successfully address this emerging threat.

## **2. What is ocean acidification?**

### *2.1 Human activities release carbon dioxide*

Data from ice cores have shown that CO<sub>2</sub> concentrations in the atmosphere have varied between 200 and 300 parts per million (ppm) over the last 400,000 years when significant anthropogenic forcing was absent (Petit et al. 1999). However, over the last two and a half centuries, human

---

<sup>1</sup> Additional pH-lowering processes, such as deposition of nitrogen and sulfur species from fossil fuel burning and agriculture, act primarily in nearshore regions and are explored elsewhere (Doney et al. 2007; Hunter et al. 2011). These processes are subject to different policy instruments not discussed here.

activities such as the burning of fossil fuels and changes in land use practices have resulted in atmospheric CO<sub>2</sub> levels sharply increasing. From 1970 to 2000, CO<sub>2</sub> concentrations in the atmosphere increased at a rate of approximately 1.5 ppm annually and since 2000 these increases have accelerated to approximately 2.2 ppm per year (US Department of Commerce). This means that not only has the total content of CO<sub>2</sub> in the atmosphere continually increased, but the rate at which it is increasing is also accelerating.

Currently, 9 petagrams (Pg) of anthropogenic CO<sub>2</sub> are released into the atmosphere every year (US Department of Commerce), which is equivalent to the mass of approximately three billion mid-sized automobiles. Of this, approximately 7.5 Pg come directly from the burning of fossil fuels and other industrial processes that emit CO<sub>2</sub>. The remaining 1.5 Pg are due to changes in land use practices, such as deforestation and urbanization (US Department of Commerce). Normally, terrestrial ecosystems, such as forests, grasslands and peatlands provide an important natural sink for atmospheric CO<sub>2</sub> by removing it from the air during photosynthesis. When human activity destroys portions of this biomass through urbanization or land-use changes, the sink no longer exists, and the result is an accumulation of additional CO<sub>2</sub> in the atmosphere. Of the 9 Pg of anthropogenically produced CO<sub>2</sub> emitted each year, approximately 2.6 Pg (or 29%) are incorporated into terrestrial plant matter (Le Quere et al. 2009). Another 4.2 Pg (or 46%) are retained in the atmosphere, which has already led to several degrees of warming around the planet. The remaining 2.3 Pg (or 26%) are absorbed by the World's oceans, resulting in an oceanic uptake of over  $146 \pm 20$  Peta-grams (Pg) of carbon (updated from Sabine and Feely 2007) since the beginning of the Industrial Revolution.

## *2.2 Ocean uptake of atmospheric carbon dioxide*

In the last three decades, a precipitous decrease in oceanic pH has been recorded at time-series locations worldwide (e.g., Bates and Peters 2007; Dore et al. 2009; Orr 2011) and during repeat ocean transects in both the Atlantic and Pacific Oceans (Byrne et al. 2010). These contemporary changes have been observed across all of the major ocean basins, confirming the global decrease in pH (e.g., NOAA PMEL Carbon Program). The pH decline is caused by the ocean's uptake of anthropogenically released CO<sub>2</sub> (National Research Council 2010). When the ocean absorbs one

CO<sub>2</sub> molecule, chemical reactions between CO<sub>2</sub> and water produce two positively charged hydrogen ions. The more hydrogen ions produced, the lower the seawater pH becomes. The positively charged hydrogen ions also react with the negatively charged bases that buffer, or stabilize, the pH of the water. (Detailed reviews of CO<sub>2</sub> solution chemistry can be found in, e.g., Gattuso and Hansson 2011; National Research Council 2010) One of these bases is the carbonate ion, which is necessary for shell and skeletal growth in marine calcifying organisms. Presently, both pH and carbonate ion concentration are dropping everywhere in the global oceans, even though the average pH of the ocean previously remained fairly constant between 8.0 and 8.2 over the past 25 million years (Ridgwell and Zeebe 2005).

If CO<sub>2</sub> emissions are left unchecked, the average ocean pH could fall below 7.8 by the end of this century, which is well outside the range of any other time in recent geological history (Feely, Doney, and Cooley 2009)<sup>2</sup>. During the past two hundred and fifty years the average oceanic pH has already decreased by a total of approximately 0.1 units, which represents a 30% increase in the hydrogen ion concentration in seawater. However, the major portion of this change has occurred in the last half-century because of accelerating CO<sub>2</sub> emission rates. Model forecasts suggest that the rate of change in ocean pH in the coming decades will be as fast as, or faster than, that of today (National Research Council 2010).

Air-sea exchange of CO<sub>2</sub> across the ocean surface plus slow overturning oceanic circulation has confined the accumulation of anthropogenic CO<sub>2</sub> to the upper 10% of the ocean's water column in most places (Sabine et al. 2004). This means that the most dramatic changes in pH and carbonate ion concentration have occurred in ocean areas where the greatest biological activity and diversity are located. Indeed, if CO<sub>2</sub> emission rates continue to rise as projected, the average pH of the surface ocean will decrease by another 0.3 – 0.4 units by 2100. However, regional factors such as coastal upwelling (Feely et al. 2008), eutrophication (Feely et al. 2010) changes in riverine and glacial discharge rates (Mathis, Cross, and Bates 2011) and sea ice loss

---

<sup>2</sup> Because seawater has a natural buffering capacity against changes in pH due to high concentrations of negatively charged bases, the average pH of marine waters is not likely to ever drop below 7.0 on the pH scale.

(Yamamoto-Kawai et al. 2009) have created many areas that are even more susceptible to large changes in pH, particularly in western boundary current regions and in the high latitude oceans.

### **3. Ocean acidification's effects on marine life**

#### *3.1 Individuals*

Recent experiments have shown that increased CO<sub>2</sub> concentrations and the accompanying changes in ocean chemistry may alter species composition, abundance, and health (Gattuso and Hansson 2011). Such impacts could be felt by both calcifying and non-calcifying primary producers and microbes and could disrupt certain biogeochemical cycles, such as nitrogen cycling or iron bioavailability, which are critical for growth. For these reasons, OA could profoundly impact the most fundamental chemical and biological processes of marine ecosystems in the coming decades (Doney et al. 2012).

The responses of both calcifying and non-calcifying organisms are by no means uniform. Initial research on calcifying organisms has focused primarily on the rate of calcification, which slows as the hydrogen ions produced during CO<sub>2</sub> dissolution reduce carbonate ion concentrations. In some cases, when too few carbonate ions are available for adequate shell building, calcifying organisms begin to dissolve (e.g., Feely et al. 2004; Fabry et al. 2008). As more studies have exposed organisms to varying pH and carbonate ion levels for short periods of time (often weeks to months), a wider range of responses has become apparent (Kroeker et al. 2010). In addition to changes in calcification, the most recent documented effects on individuals include things like delayed development, which in some cases increases or prolongs exposure to predators (Talmage and Gobler 2010; Gaylord et al. 2011); impacts on behavior, such as poorer detection of predators or prey (Cripps, Munday, and McCormick 2011; Nilsson et al. 2012), decreased recruitment and/or larval survival (e.g., Albright and Langdon 2011; Crim, Sunday, and Harley 2011); and even direct tissue damage in some non-calcifying species (Frommel et al. 2012). Susceptibility of individual organisms, species, or strains to these effects varies (Kroeker et al. 2010; Ries, Cohen, and McCorkle 2009). Research currently focuses on identifying the physiological mechanisms behind the variety of observed responses (Gattuso and Hansson 2011)

Some species appear to be able to tolerate changes in pH and carbonate ion concentrations, at least on short-term intervals. Some species may also be better able than others to adapt to changing pH levels due to their exposure to environments where pH naturally varies over a wide range. Because of this, there will likely be ecological “winners” and “losers” as local competition for resources plays out on top of direct effects on species from ocean acidification. Depending on the region, this could lead to changes in ecosystem structure (e.g., Fabricius et al. 2011) and possible species migration to more suitable habitats, or in the worst-case scenario, a complete regime shift (e.g., Hare and Mantua 2000) in which there is a rapid reorganization of an ecosystem from one relatively stable state to another. These shifts may last for several decades, producing a high degree of interannual variability in the marine system and in some cases, may reduce economic viability of a region (Cooley et al. 2012). However, at this point it is still very uncertain what the ecological and societal consequences will be from any potential losses of keystone species, and how the “winners” will impact the ecosystem or the biogeochemical cycles as a whole. There are places in the ocean where CO<sub>2</sub> levels are naturally high (i.e. volcanic CO<sub>2</sub> vents). These ecosystems provide a glimpse of what parts of the ocean may look like in the future. In these naturally CO<sub>2</sub> rich areas photosynthetic species, such as sea grasses, thrive, but the biodiversity in these systems is 30% less than comparable regions with “normal” CO<sub>2</sub> levels (Hall-Spencer et al. 2008).

### *3.2 Communities*

The changes in ocean temperature and pH occurring as a result of human activities are altering the physiology, behavior, and demography of individual marine organisms, which subsequently change how these populations interact with others and their environment. This reshapes the community in both bottom-up (resource-controlled) and top-down (predator-controlled) directions (Doney et al. 2012). Recent ecosystem-scale research strongly suggests that OA reduces the diversity, biomass, and food-web complexity of benthic marine ecosystems (Kroeker et al. 2011; Hall-Spencer et al. 2008; Hoegh-Guldberg et al. 2007), although this work is still at an early stage, involving only a limited number of species. At naturally occurring volcanic CO<sub>2</sub> vents, studies conducted to examine how benthic communities respond to long-term lower-pH,

CO<sub>2</sub>-enriched conditions report that biodiversity decreased with pH (Kroeker et al. 2011; Hall-Spencer et al. 2008; Cigliano et al. 2010). Local disturbances such as coral bleaching, disease, and destructive fishing are pressuring coral reef systems to become dominated by macroalgae (Hoegh-Guldberg et al. 2007); global disturbances such as acidification and warming are expected to exert similar pressure on coral reefs. Conversion of coral-dominated systems to macroalgal-dominated systems may involve crossing a “tipping point” which may be difficult to reverse (Hoegh-Guldberg et al. 2007). It is not known how likely this is to occur in other types of non-coral benthic environments, and in future high-CO<sub>2</sub> oceans as a whole.

By altering seawater pH and carbonate ion levels, ocean acidification can also change cycles of major and minor nutrients other than carbon. For instance, culture-based microbial studies suggest that OA may markedly alter nitrogen cycling. Nitrogen fixation that converts nitrogen gas (N<sub>2</sub>) to ammonium (NH<sub>3</sub> and NH<sub>4</sub><sup>+</sup>) could increase under higher CO<sub>2</sub>, enlarging the pool of reduced nitrogen in the ocean (Hutchins, Mulholland, and Fu 2009). Nitrification, which oxidizes ammonium to phytoplankton-nourishing nitrate (NO<sub>3</sub>), is believed to decrease in response to lower pH (Hutchins, Mulholland, and Fu 2009; Beman et al. 2011). Denitrification, which reduces NO<sub>3</sub> to nitrogen gas, occurs in anaerobic environments where pCO<sub>2</sub> is already high and pH is subsequently low, so OA is not anticipated to dramatically alter the process (Hutchins, Mulholland, and Fu 2009). If changes in the nitrogen cycle are not balanced, reduced nitrogen, in the form of ammonium, could accumulate in the oceans and promote a larger microbial community at the expense of higher trophic levels (Hutchins, Mulholland, and Fu 2009). The effect of OA on most minor nutrients has not been determined, but pH affects the speciation of inorganic metals, which can either act as nutrients or toxins on phytoplankton. Copper, for example, may be more toxic in lower-pH waters, whereas iron may be more bioavailable as a micronutrient (Millero et al. 2009).

Ocean acidification is most likely to occur in combination with several anthropogenically linked marine stressors, including other global-scale stressors such as warming and deoxygenation, leading to synergies that are still being explored. Studies to date show possible links between OA and deoxygenation (Keeling, Körtzinger, and Gruber 2010). Ocean acidification could alter elemental ratios in organic matter, decrease calcification, and/or increase nitrogen fixation, all of

which would require more oxygen to remineralize organic material, which would occur at shallower depths (Gruber 2011). Furthermore, higher oceanic CO<sub>2</sub> levels accompanied by low oxygen levels could increase respiratory stress of many organisms and decrease thermal tolerance of some, while higher temperatures would further increase oxygen demand and additionally stress marine organisms (Gruber 2011).

Ocean acidification's effects on marine ecosystems, whether acting alone or synergistically with other stressors, will affect human communities by altering the benefits that marine systems provide (Cooley In press; Cooley, Kite-Powell, and Doney 2009). These benefits, or ecosystem services, can be grouped into four major categories: supporting services, provisioning services, regulating services, and cultural services (Millennium Ecosystem Assessment 2005).

Provisioning services, like the availability of food, water, fiber, and fuel, are the marine ecosystem services that are most often quantified because they have market values attached to them. Ocean acidification's effects on these services have begun to be assessed in a series of economically based investigations (Cooley and Doney 2009; Cooley et al. 2012; Narita, Rehdanz, and Tol 2012; Armstrong et al. 2012). In addition to endangering mollusk-harvest-related economic revenues for many nations, OA could endanger food security for some nations (Cooley et al. 2012), especially developing island nations. At the same time, supporting services (e.g., nutrient cycling, photosynthesis, habitat creation), regulating services (e.g., purifying water, storing carbon, protecting coastlines, and regulating climate) and cultural services (e.g. providing recreational, aesthetic, spiritual benefits), also depend on species that are directly vulnerable to OA, including coral, mollusks, and planktonic species.

#### **4. Addressing ocean acidification**

##### *4.1 Future Emission Scenarios*

Although there are several anthropogenic factors influencing pH change and the reduction of carbonate mineral concentrations in some parts of the ocean, the release of CO<sub>2</sub> into the atmosphere is the major global driver. As CO<sub>2</sub> concentrations increase in the atmosphere, the

pH of the ocean will continue to drop. However, even if all CO<sub>2</sub> emissions were eliminated, the pH of the ocean would continue to decline for anywhere between several decades to hundreds of years due to the accumulation of CO<sub>2</sub> in the atmosphere that has already occurred. The longer CO<sub>2</sub> emissions go unchecked, the more “momentum” will build in the atmosphere to drive ocean acidification. This is very disconcerting in a world where over 75% of all energy production is derived from burning fossil fuels. Up until 2005, the USA was the top emitter of CO<sub>2</sub>, releasing roughly 1.6 million tons annually (U.S. Energy Information Administration 2009). Recently, China has now surpassed the USA in total emissions and as of 2007 their discharge rates had passed 1.8 million tons of CO<sub>2</sub> per year. Other industrial nations, such as India, Russia, and Japan, are all well behind the USA and China in their emission rates. However, vast segments of the global population that have previously had little to no impact on global anthropogenic CO<sub>2</sub> production are industrializing at a very rapid rate. In China, the per capita production of CO<sub>2</sub> is only 25% of what Americans produce, indicating that there is a great potential for an exponential increase in CO<sub>2</sub> emissions as Chinese energy consumption grows (Carbon Dioxide Information Analysis Center 2012).

During the last two decades, over 440 million Chinese (more than the total population of the USA) have become significant energy consumers and CO<sub>2</sub> emitters through increases in electricity usage and automobile ownership. This accounts for China’s ascent to the top ranks of global CO<sub>2</sub> emitters, but there are hundreds of millions more people across Asia and Africa that are not far behind in their demand for western-style energy consumption rates. Even as the international community struggles to develop mitigation plans, the momentum in the global economy that is driving increased fossil fuel usage will be difficult to overcome without a radically new clean (CO<sub>2</sub> free) source of energy. As a result, it unfortunately appears that OA is a problem that is here to stay for a while.

#### *4.2 Mitigation Options*

Broad mitigation of CO<sub>2</sub> emissions is the only approach that will prevent extensive OA. Until that can be achieved, several geoengineering options have been proposed for increasing marine pH or carbonate ion levels. At the moment many of these appear costly and are likely to only be

applicable on small scales, but research is needed to determine exactly how these can help (Rau, McLeod, and Hoegh-Guldberg 2012). One of the more promising solutions utilizes electrochemistry (Rau 2008) to split calcium carbonate and increase the alkalinity in a region. While this would work in enclosed or partially enclosed systems, it would be impractical to apply over a broad area or maintain over a long period. A variation on this approach involves electrochemically titrating hydrochloric acid from the ocean and neutralizing it with silicate rocks (House et al. 2007). Other suggestions include directly adding lime to the ocean or creating artificial limestone reefs to encourage settlement from natural reefs that are struggling under acidified conditions. As with electrochemical mitigation, these options could help offset OA in a particular locale, but global reduction of CO<sub>2</sub> emissions will be more efficient than many scattered regional geoengineering installations. Long-term, global use of these geoengineering options is not practical, given the energy required to conduct them (e.g., mining terrestrial lime) and the sheer volume of ocean water that would need to be continuously modified to compete with the continued CO<sub>2</sub> invasion that will likely accompany further human development.

The only process that will completely return the pH of the ocean to its preindustrial state and remove all the anthropogenic CO<sub>2</sub> from the atmosphere is the addition of carbonate minerals to the ocean from natural erosion and weathering processes. However, this will be slow. Hundreds of thousands, if not millions of years, will be required to undo the CO<sub>2</sub> released by two centuries of industrial activity. The longer we wait to implement broad-scale CO<sub>2</sub> mitigation efforts, the more ocean pH will decrease, and the longer it will take to undo the damage that has already been done.

#### *4.3 Adaptation Options*

Although mitigating CO<sub>2</sub> levels in the atmosphere and ocean may not be practical on regional scales, there are other regional adaptations that can help protect marine ecosystems to some extent from the consequences of OA. Employing many of these strategies at once may help keep sensitive areas of the marine economy stable. Not only will these adaptations help human communities successfully deal with the first appearance of OA impacts, but they are thought to

also contribute to healthier marine ecosystems overall that can better withstand the chronic stresses of OA and climate change by promoting biodiversity (e.g., Mora et al. 2011).

Monitoring OA-relevant parameters in seawater in more locations globally provides insight into typical levels of water chemistry variability, and it can also provide early warning when conditions exit this natural range. The benefit of monitoring can be demonstrated with a case study of the oyster hatcheries along the coast of the U.S. Pacific Northwest, which observed repeated harvest failures in recent years (Barton et al. 2012). These hatcheries supply the majority of the oyster spat to farms all across the United States, but they nearly went out of business as they unknowingly pumped acidified water, corrosive to oyster larvae, into their operation during natural upwelling events. An intensive research program and industry-research partnerships led to new innovations that allow these hatcheries to monitor the pH of the incoming water, shutting down their intakes when upwelling events deliver low pH water to coastal regions. This simple adaptation saved an industry (Barton et al. 2012). The successful use of OA monitoring at the West Coast hatcheries has led to the development of an international ocean acidification monitoring network, endorsed by a number of funding agencies and NGOs, as a short- to medium-term adaptation for dealing with the consequences of OA. This network of moorings will return CO<sub>2</sub>, pH, temperature, and oxygen data in real-time to shore based facilities where ocean conditions can be continuously monitored. The data will be available to stakeholders as well as state and federal agencies to manage resources along the coast. The OA network will function much in the same way as a weather bureau does, providing early warnings and forecast for ocean conditions so that communities and industry can prepare for threatening events (i.e. intense coastal upwelling).

Additionally, managing terrestrial substances that reach marine systems via rainwater, rivers, and groundwater can reduce or eliminate many marine stressors. Preventing runoff of nutrients and silt from terrestrial communities will limit shading or smothering of sessile coastal species, like corals or shellfish beds (Bryant et al. 1998). Controlling nutrient runoff will also prevent the development of hypoxic conditions that follow algal overgrowth, and it will help keep major and minor nutrient cycles within normal limits for healthy coastal ecosystems (Howarth et al. 2012). Maintaining freshwater runoff at near-natural levels will also keep coastal ecosystems resilient;

too much runoff can cause erosion, siltation, nutrient overloading, and vertical stratification in coastal waters, whereas too little runoff can dry up rivers and estuaries, leading to salinity intrusion, nutrient loading, and ecosystem disruptions. Finally, atmospheric pollutants from fossil fuel burning that dissolve in rainwater, like sulfur dioxide, further disrupt the pH of nearshore regions (Doney et al. 2007; Hunter et al. 2011; Doney 2010). In addition to enacting specific policies regulating the processes mentioned above, communities can plan coastal development carefully to reduce the likelihood of these processes happening accidentally.

Integrated management of in situ marine resources themselves can also reduce the stressors acting on the entire marine ecosystem. Eliminating destructive fishing such as bottom trawling over vulnerable habitat (shallow corals, deep sea corals, or seagrass) and physical disruption of benthic environments by coastal users results in greater biodiversity and resilience in coastal marine ecosystems. Similarly, ecosystem-based management that takes into account the current and future physical and chemical environment, the local food web, and the population dynamics of harvestable species results in more diverse ecosystems that can withstand some level of perturbation without crossing an ecosystem threshold into a completely different state (e.g., Hoegh-Guldberg et al. 2007; Hare and Mantua 2000). Restoring substrate by returning oyster shells to productive beds and building artificial reefs (with objects or electrochemically deposited limestone) can also encourage larval (re)settlement of a variety of benthic species, maintaining diversity that could otherwise be lost owing to decreased physical habitat. A side benefit of maintaining diverse, healthy ecosystems with appropriate levels of physical habitat includes maintaining or increasing coastal protection, by creating structures that dissipate wave energy reaching land or protect seafloors from storm scouring.

Some specific adaptations can be employed to minimize the effects of OA on marine harvests and aquaculture. We know that there will be “winners” and “losers” in the future high-CO<sub>2</sub> ocean (National Research Council 2010), so marine harvests and in-situ aquaculture can be adjusted to sustainably exploit winning species (Parker, Ross, and O’Connor 2011). For economically or nutritionally valuable species that can be cultured, “smart” aquaculture techniques can be employed, including protecting vulnerable life stages, increasing production of larvae or juveniles to ensure reasonable recruitment levels, or developing closed aquaculture

systems (perhaps including polyculture) in which water conditions can be tightly controlled. Some of these have already been proven in the oyster hatcheries in the U.S. Pacific Northwest.

Marine policies that support adaptations to OA may govern the use or conservation of marine resources. Most commonly considered is fishery policy, which sets harvest limits, permitted areas, and open seasons. As discussed above, ecosystem-based policies that consider the whole system will be flexible enough to handle OA in conjunction with other stressors. But a more subtle challenge involves developing these policies in geographically flexible formats: there is a need for harvest policies that can handle migration of target species over multiple years due to environmental change. Similarly, marine protected areas (MPAs) will need to be chosen with future change in mind. Establishing an MPA in a region expected to experience rapid environmental change will be fruitless, whereas establishing one where temperature or pH will change very little may be a better choice for conserving certain species.

Policies supporting adaptation measures may also relate to the human communities that depend on marine resources. Certain coastal communities may be more sensitive to negative effects caused by OA and climate change, because of their dependence on ecosystem services vulnerable to global change (e.g., Cooley et al. 2012). Planners therefore need to enact customized policies for each region. Nevertheless, some general characteristics can be identified. First, decision makers can enact policies that lead towards economic and nutritional diversification. Just like some marine ecosystems with low biodiversity, human communities with low economic or nutritional diversity are more at risk of major disruption due to environmental stressors. Supportive policies may involve offering low-cost loans or tax incentives to businesses that undertake steps towards adapting to OA. Business-related steps could involve developing industry consortia or cooperative arrangements that pool material or economic resources to undertake adaptive aquaculture on a larger, more efficient scale; retraining workers displaced by contraction of industries due to losses associated with OA; or promoting industry-research partnerships to develop early warning systems, aquaculture of resilient species or strains, or new technology to mitigate local acidification. In some cases, technology or knowledge transfer may be necessary from developed to developing nations, to

help the most vulnerable communities implement effective plans for adapting to OA and global change.

As citizens and consumers, individuals can take steps that will help marine ecosystems adapt to OA. People can participate in community decision making by voting, providing feedback to elected officials on marine-relevant policies and decision points, and helping set community priorities and future goals. While remaining active in the community on marine-relevant topics, citizens can also contribute to overall marine and coastal health by making lifestyle choices and purchases that reduce pressure on marine ecosystems. Examples of this that even non-coastal residents could undertake could include reducing one's "carbon footprint"; using less plastic and creating less plastic waste; purchasing seafood that is sustainably harvested; avoiding marine products (such as coral jewelry or wild-caught saltwater aquarium fish) that further damage OA-vulnerable species; and consuming species that are OA and climate-resilient as they are identified. Other examples relevant for coastal residents and tourists include participating in non-damaging recreation around coral reefs and other unique benthic environments, eliminating pollution from boats, sewer systems, and residential fertilizer and pesticide runoff; and limiting freshwater runoff from private property. By learning about the upstream and downstream consequences of their choices, citizens can choose activities and products that have smaller impacts on the land-ocean system. Although many of these adaptive activities do not directly mitigate OA, they reduce other, more easily adjustable stressors on marine species and contribute to the overall health of marine systems.

## **5. International policy**

### *5.1 Relevance to MDGs*

To improve socioeconomic conditions worldwide, the United Nations has established eight Millennium Development Goals (MDGs) to be achieved by 2015 (United Nations 2002b). But OA poses a direct challenge to some of the MDGs by endangering marine biodiversity, mollusk

harvests, and recreational opportunities associated with coral reefs. The goal of ending poverty and hunger (#1) could be derailed by OA-driven losses of high-quality protein and income from mollusks (Cooley et al. 2012) and other vulnerable species important in commercial and subsistence fisheries worldwide. The goal of ensuring environmental sustainability (#7) could be challenged by loss of environmental resources such as specific marine habitats (like reefs) and biodiversity (Hofmann et al. 2010), both of which are relevant to Targets 7A and C. The goal of creating a global partnership for development (#8) could be challenged by the specific nutrition- and income-related hardships caused by OA, which will likely disproportionately impact the least developed countries and small island states (Cooley et al. 2012), which are relevant to Targets 8B and C. By reducing people's access to high-quality nutrition and income, OA could also pose indirect challenges to aspects of other health- and economically-linked goals, such as reducing child mortality (#4), reducing poverty to promote gender equality (#3), and improving maternal health via nutrition and poverty alleviation.

## *5.2 Relevance to UNFCCC*

Because OA and climate change are both driven by atmospheric CO<sub>2</sub>, international processes and mechanisms can be applied to both problems simultaneously. Much discussion has focused on using UNFCCC to address OA, given its goal of stabilizing atmospheric concentrations of greenhouse gases. However, since the UNFCCC focuses on a range of radiatively active gases to address changes in climate, it may need some adjustments to address OA meaningfully (Harrould-Kolieb and Herr 2012). First, decision makers must focus on reducing CO<sub>2</sub> and not just other greenhouse gases such as methane that may be easier to regulate and which are given equal importance in documents such as the Clean Development Mechanism (Harrould-Kolieb and Herr 2012). Similarly, any geoengineering plan designed to combat climate change should also reduce OA simultaneously (Figure 1). Including OA in UNFCCC would also promote the development of formal monitoring and research plans for OA at national and international levels, provide common metrics for measuring OA, and perhaps even establish targets. UNFCCC offers one of the best opportunities to mitigate OA as it is an international accord; only a global effort can truly address this problem effectively.

## 6. Summary

Although sustainable development activities look primarily towards the future to set a course of environmentally friendly action based on current best practices, they must be planned within the environmental and social framework created by past activities. The legacy of human development has created present-day conditions that are far from perfect, including global processes such as climate change and OA. Both of these processes are rooted in human emissions of carbon dioxide to the atmosphere, resulting from heavy use of fossil fuels and changes in land use.

Ocean acidification is an emerging issue of concern; although chemists have long recognized that oceanic uptake of carbon dioxide is a key mechanism regulating the Earth's carbon cycle, the effect of this process on many marine ecosystems is only just beginning to be understood. Ocean acidification-sensitive species that we know about include shellfish and corals with hard calcium carbonate shells and skeletons, animals with high metabolic and respiratory requirements such as giant squid, and animals with behavioral and physiological functions that depend on a narrow range of seawater chemistry. Marine ecosystems that rely on these organisms, which includes nearly every ecosystem worldwide are likely to be subtly or overtly reshaped as OA inevitably progresses, due to the current burden of atmospheric CO<sub>2</sub> that is being enhanced by ongoing, accelerating emissions. The resulting consequences on human communities that depend heavily on marine resources could also be subtle or profound, with many indirect connections to overall global human well-being.

International efforts currently focus mostly on the long-term, large-scale goal of reducing atmospheric CO<sub>2</sub> emissions. Achieving this goal will contribute greatly to sustainable development. However, there are specific regional opportunities that humans can pursue in the meantime that will yield a better understanding of ocean acidification's effects and lower stresses on marine resources overall. Monitoring water chemistry will afford insight into the extent and

pace of acidification, contributing to the development of “early warning systems” when possible. Reducing other regionally controllable stressors on shorter terms, like nutrient, water, and silt runoff, while managing marine resource use in holistic terms, will contribute to greater marine ecosystem resilience. Identifying resilient species, or the factors that contribute to resilience, will allow humans to identify ways to preserve the flow of benefits from marine resources within the environmental limits that are being set by climate change and acidification. Finally, considering the patterns of human dependence on marine resources may uncover alternatives for people whose livelihoods or nourishment options are being modified due to environmental change.

Ocean acidification represents a challenge to the current framework of sustainable development, because it has roots in the past and will reach into the future despite our efforts to control its source. While the mitigation and ultimately the elimination of CO<sub>2</sub> emissions into the environment should be the primary objective of the international community, we have to be realistic about what can be achieved over the next several decades as green energy alternatives continue to evolve. It is unlikely that the intensive cuts in global CO<sub>2</sub> emissions necessary to avoid some ocean acidification impacts will be realized in the near-term because of political reasons and a lack of viable energy alternatives. Therefore, the global community must look towards pragmatic solutions to alleviate ocean stressors as much as possible so that the impacts from ocean acidification can be better tolerated by marine organisms. Although many of the adaptation and geoengineering solutions are costly and may only have regional impacts, the effort must be made nonetheless. Addressing ocean acidification as part of sustainable development by acknowledging it, researching it, and seeking an array of nested solutions will allow human communities to live with the legacy of previous development and plan for the future while ensuring equity for all.

## References

- Albright, Rebecca, and Chris Langdon. 2011. “Ocean acidification impacts multiple early life history processes of the Caribbean coral *Porites astreoides*.” *Global Change Biology* 17 (7) (July): 2478–2487. doi:10.1111/j.1365-2486.2011.02404.x.

- Armstrong, C.W., S. Holen, S. Navrud, and A. Seifert. 2012. *The Economics of Ocean Acidification -- a Scoping Study*. Frams Center, Norway. <http://www.framsenteret.no/the-economics-of-ocean-adification-a-scoping-study.5053197-143877.html>.
- Asilomar Scientific Organizing Committee. 2010. *The Asilomar Conference Recommendations on Principles for Research into Climate Engineering Techniques Conference Report*. Washington, D.C.: Climate Institute.
- Barton, Alan, Burke Hales, George G. Waldbusser, Chris Langdon, and Richard A. Feely. 2012. "The Pacific Oyster, *Crassostrea Gigas*, Shows Negative Correlation to Naturally Elevated Carbon Dioxide Levels: Implications for Near-term Ocean Acidification Effects." *Limnology and Oceanography* 57 (3): 698–710. doi:10.4319/lo.2012.57.3.0698.
- Bates, Nicholas R., and Andrew J Peters. 2007. "The Contribution of Atmospheric Acid Deposition to Ocean Acidification in the Subtropical North Atlantic Ocean." *MARINE CHEMISTRY* 107 (4) (December 20): 547–558. doi:10.1016/j.marchem.2007.08.002.
- Beman, J. Michael, Cheryl-Emiliane Chow, Andrew L. King, Yuanyuan Feng, Jed A. Fuhrman, Andreas Andersson, Nicholas R. Bates, Brian N. Popp, and David A. Hutchins. 2011. "Global Declines in Oceanic Nitrification Rates as a Consequence of Ocean Acidification." *Proceedings of the National Academy of Sciences* 108 (1) (January 4): 208–213. doi:10.1073/pnas.1011053108.
- Bryant, Dirk, Lauretta Burke, John McManus, and Mark Spalding. 1998. *Reefs at Risk: A Map-Based Indicator of Threats to the World's Coral Reefs*. World Resources Institute. <http://www.wri.org/publication/reefs-at-risk>.
- Byrne, Robert H, Sabine Mecking, Richard A Feely, and Xuewu Liu. 2010. "Direct Observations of Basin-wide Acidification of the North Pacific Ocean." *GEOPHYSICAL RESEARCH LETTERS* 37 (January 20). doi:10.1029/2009GL040999.
- Carbon Dioxide Information Analysis Center. 2012. "Ranking of the World's Countries by 2008 Per Capita Fossil Fuel Emission Rates." <http://cdiac.ornl.gov/trends/emis/top2008.cap>.
- Cigliano, M., M. Gambi, R. Rodolfo-Metalpa, F. Patti, and J. Hall-Spencer. 2010. "Effects of Ocean Acidification on Invertebrate Settlement at Volcanic CO<sub>2</sub> Vents." *Marine Biology* 157 (11): 2489–2502. doi:10.1007/s00227-010-1513-6.
- Cooley, Sarah R. In press. "How Human Communities Could 'Feel' Changing Ocean Biogeochemistry." *Current Opinion in Environmental Sustainability*
- Cooley, Sarah R., and Scott C. Doney. 2009. "Anticipating Ocean Acidification's Economic Consequences for Commercial Fisheries." *Environmental Research Letters* 4 (2) (June): 024007. doi:10.1088/1748-9326/4/2/024007.
- Cooley, Sarah R., Hauke L. Kite-Powell, and Scott C. Doney. 2009. "Ocean Acidification's Potential to Alter Global Marine Ecosystem Services." *Oceanography* 22 (4): 172–181.
- Cooley, Sarah R., Noelle Lucey, Hauke L. Kite-Powell, and Scott C. Doney. 2012. "Nutrition and Income from Mollusks Today Imply Vulnerability to Ocean Acidification Tomorrow." *FISH AND FISHERIES* 13 (2): 182–215. doi:10.1111/j.1467-2979.2011.00424.x.
- Crim, Ryan N., Jennifer M. Sunday, and Christopher D. G. Harley. 2011. "Elevated seawater CO<sub>2</sub> concentrations impair larval development and reduce larval survival in endangered northern abalone (*Haliotis kamtschatkana*)." *Journal of Experimental Marine Biology and Ecology* 400 (1-2) (April 30): 272–277. doi:10.1016/j.jembe.2011.02.002.

- Cripps, Ingrid L., Philip L. Munday, and Mark I. McCormick. 2011. "Ocean Acidification Affects Prey Detection by a Predatory Reef Fish." *PLoS ONE* 6 (7) (July 28): e22736. doi:10.1371/journal.pone.0022736.
- Doney, Scott C. 2010. "The Growing Human Footprint on Coastal and Open-Ocean Biogeochemistry." *Science* 328 (5985) (June 18): 1512–1516. doi:10.1126/science.1185198.
- Doney, Scott C., Natalie Mahowald, Ivan Lima, Richard A. Feely, Fred T. Mackenzie, Jean-Francois Lamarque, and Phil J. Rasch. 2007. "Impact of Anthropogenic Atmospheric Nitrogen and Sulfur Deposition on Ocean Acidification and the Inorganic Carbon System." *Proceedings of the National Academy of Sciences* 104 (37) (September): 14580–14585. doi:10.1073/pnas.0702218104.
- Doney, Scott C., Mary Ruckelshaus, J. Emmett Duffy, James P. Barry, Francis Chan, Chad A. English, Heather M. Galindo, et al. 2012. "Climate Change Impacts on Marine Ecosystems." In *Annual Review of Marine Science, Vol 4*, ed. C. A. Carlson and S. J. Giovannoni, 4:11–37. Palo Alto: Annual Reviews.
- Dore, John E, Roger Lukas, Daniel W Sadler, Matthew J Church, and David M Karl. 2009. "Physical and Biogeochemical Modulation of Ocean Acidification in the Central North Pacific." *PROCEEDINGS OF THE NATIONAL ACADEMY OF SCIENCES OF THE UNITED STATES OF AMERICA* 106 (30) (July 28): 12235–12240. doi:10.1073/pnas.0906044106.
- Fabricius, Katharina E., Chris Langdon, Sven Uthicke, Craig Humphrey, Sam Noonan, Glenn De'ath, Remy Okazaki, Nancy Muehllehner, Martin S. Glas, and Janice M. Lough. 2011. "Losers and Winners in Coral Reefs Acclimatized to Elevated Carbon Dioxide Concentrations." *Nature Climate Change* 1 (3): 165–169. doi:10.1038/nclimate1122.
- Fabry, Victoria J, Brad A Seibel, Richard A Feely, and James C Orr. 2008. "Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes." *ICES JOURNAL OF MARINE SCIENCE* 65 (3) (April): 414–432. doi:10.1093/icesjms/fsn048.
- Feely, Richard A, Simone R Alin, Jan Newton, Christopher L Sabine, Mark Warner, Allan Devol, Christopher Krembs, and Carol Maloy. 2010. "The Combined Effects of Ocean Acidification, Mixing, and Respiration on pH and Carbonate Saturation in an Urbanized Estuary." *ESTUARINE COASTAL AND SHELF SCIENCE* 88 (4) (August 10): 442–449. doi:10.1016/j.ecss.2010.05.004.
- Feely, Richard A, Scott C Doney, and Sarah R Cooley. 2009. "Ocean Acidification: Present Conditions and Future Changes in a High-CO<sub>2</sub> World." *Oceanography* 22 (4, Sp. Iss. SI) (December): 36–47.
- Feely, Richard A, Christopher L Sabine, J. Martin Hernandez-Ayon, Debby Ianson, and Burke Hales. 2008. "Evidence for Upwelling of Corrosive 'acidified' Water onto the Continental Shelf." *SCIENCE* 320 (5882) (June 13): 1490–1492. doi:10.1126/science.1155676.
- Feely, Richard A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, and F. J. Millero. 2004. "Impact of Anthropogenic CO<sub>2</sub> on the CaCO<sub>3</sub> System in the Oceans." *SCIENCE* 305 (5682) (July 16): 362–366.
- Frommel, Andrea Y., Rommel Maneja, David Lowe, Arne M. Malzahn, Audrey J. Geffen, Arild Folkvord, Uwe Piatkowski, Thorsten B. H. Reusch, and Catriona Clemmesen. 2012. "Severe tissue damage in Atlantic cod larvae under increasing ocean acidification." *Nature Climate Change* 2 (1) (January): 42–46. doi:10.1038/CLIMATE1324.

- Gattuso, Jean-Pierre, and Lina Hansson. 2011. *Ocean Acidification*. Oxford, UK: Oxford University Press.
- Gaylord, Brian, Tessa M. Hill, Eric Sanford, Elizabeth A. Lenz, Lisa A. Jacobs, Kirk N. Sato, Ann D. Russell, and Annaliese Hettinger. 2011. "Functional Impacts of Ocean Acidification in an Ecologically Critical Foundation Species." *The Journal of Experimental Biology* 214 (15) (August 1): 2586–2594. doi:10.1242/jeb.055939.
- Gruber, Nicolas. 2011. "Warming up, Turning Sour, Losing Breath: Ocean Biogeochemistry Under Global Change." *PHILOSOPHICAL TRANSACTIONS OF THE ROYAL SOCIETY A-MATHEMATICAL, PHYSICAL, AND ENGINEERING SCIENCES* 369: 1980–1996. doi:DOI: 10.1098/rsta.2011.0003.
- Hall-Spencer, Jason M, Riccardo Rodolfo-Metalpa, Sophie Martin, Emma Ransome, Maoz Fine, Suzanne M Turner, Sonia J Rowley, Dario Tedesco, and Maria-Cristina Buia. 2008. "Volcanic Carbon Dioxide Vents Show Ecosystem Effects of Ocean Acidification." *NATURE* 454 (7200) (July 3): 96–99. doi:10.1038/nature07051.
- Hare, S. R., and N. J. Mantua. 2000. "Empirical evidence for North Pacific regime shifts in 1977 and 1989." *Progress in Oceanography* 47 (2-4): 103–145. doi:10.1016/S0079-6611(00)00033-1.
- Harrould-Kolieb, Ellycia R., and Dorothée Herr. 2012. "Ocean Acidification and Climate Change: Synergies and Challenges of Addressing Both Under the UNFCCC." *Climate Policy* 12 (3): 378–389. doi:10.1080/14693062.2012.620788.
- Hoegh-Guldberg, O., P. J. Mumby, A. J. Hooten, R. S. Steneck, P. Greenfield, E. Gomez, C. D. Harvell, et al. 2007. "Coral Reefs Under Rapid Climate Change and Ocean Acidification." *Science* 318 (5857) (December 14): 1737–1742. doi:10.1126/science.1152509.
- Hofmann, Gretchen E., James P. Barry, Peter J. Edmunds, Ruth D. Gates, David A. Hutchins, Terrie Klinger, and Mary A. Sewell. 2010. "The Effect of Ocean Acidification on Calcifying Organisms in Marine Ecosystems: An Organism-to-Ecosystem Perspective." *Annual Review of Ecology, Evolution, and Systematics* 41 (1) (December): 127–147. doi:10.1146/annurev.ecolsys.110308.120227.
- House, Kurt Zenz, Christopher H House, Daniel P Schrag, and Michael J Aziz. 2007. "Electrochemical Acceleration of Chemical Weathering as an Energetically Feasible Approach to Mitigating Anthropogenic Climate Change." *ENVIRONMENTAL SCIENCE & TECHNOLOGY* 41 (24) (December 15): 8464–8470. doi:10.1021/es0701816.
- Howarth, Robert, Dennis Swaney, Gilles Billen, Josette Garnier, Bongghi Hong, Christoph Humborg, Penny Johnes, Carl-Magnus Morth, and Roxanne Marino. 2012. "Nitrogen fluxes from the landscape are controlled by net anthropogenic nitrogen inputs and by climate." *Frontiers in Ecology and the Environment* 10 (1) (February): 37–43. doi:10.1890/100178.
- Hunter, Keith A., Peter S. Liss, Vanisa Surapipith, Frank Dentener, Robert Duce, Maria Kanakidou, Nilgun Kubilay, et al. 2011. "Impacts of anthropogenic SO<sub>x</sub>, NO<sub>x</sub> and NH<sub>3</sub> on acidification of coastal waters and shipping lanes." *Geophysical Research Letters* 38 (July 7). doi:10.1029/2011GL047720.
- Hutchins, David A, Margaret R Mulholland, and Feixue Fu. 2009. "Nutrient Cycles and Marine Microbes in a CO<sub>2</sub>-Enriched Ocean." *Oceanography* 22 (4, Sp. Iss. SI) (December): 128–145.

- Keeling, Ralph F., Arne Körtzinger, and Nicolas Gruber. 2010. "Ocean Deoxygenation in a Warming World." *Annual Review of Marine Science* 2 (1) (January): 199–229. doi:10.1146/annurev.marine.010908.163855.
- Kroeker, Kristy J, Rebecca L Kordas, Ryan N Crim, and Gerald G Singh. 2010. "Meta-analysis Reveals Negative yet Variable Effects of Ocean Acidification on Marine Organisms." *Ecology Letters* 13 (11) (November 1): 1419–1434. doi:10.1111/j.1461-0248.2010.01518.x.
- Kroeker, Kristy J., Fiorenza Micheli, Maria Cristina Gambi, and Todd R. Martz. 2011. "Divergent ecosystem responses within a benthic marine community to ocean acidification." *Proceedings of the National Academy of Sciences of the United States of America* 108 (35) (August 30): 14515–14520. doi:10.1073/pnas.1107789108.
- Mathis, Jeremy T., Jessica N. Cross, and Nicholas R. Bates. 2011. "The role of ocean acidification in systemic carbonate mineral suppression in the Bering Sea." *Geophysical Research Letters* 38 (October 6). doi:10.1029/2011GL048884.
- Millennium Ecosystem Assessment. 2005. *Ecosystems and Human Well-Being: Current State and Trends: Findings of the Condition and Trends Working Group*. 1st ed. Island Press.
- Millero, Frank J, Ryan Woosley, Benjamin Ditrolio, and Jason Waters. 2009. "Effect of Ocean Acidification on the Speciation of Metals in Seawater." *Oceanography* 22 (4, Sp. Iss. SI) (December): 72–85.
- Mora, Camilo, Octavio Aburto-Oropeza, Arturo Ayala Bocos, Paula M. Ayotte, Stuart Banks, Andrew G. Bauman, Maria Beger, et al. 2011. "Global Human Footprint on the Linkage between Biodiversity and Ecosystem Functioning in Reef Fishes." *Plos Biology* 9 (4) (April). doi:10.1371/journal.pbio.1000606.
- Narita, Daiju, Katrin Rehdanz, and Richard S. J. Tol. 2012. "Economic Costs of Ocean Acidification: a Look into the Impacts on Global Shellfish Production." *Climatic Change* (January 8). doi:10.1007/s10584-011-0383-3. <http://www.springerlink.com/content/a6k337311391hn67/>.
- National Research Council. 2010. *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*. Washington, D.C.: The National Academies Press. [http://www.nap.edu/catalog.php?record\\_id=12904#toc](http://www.nap.edu/catalog.php?record_id=12904#toc).
- Nilsson, Goran E., Danielle L. Dixson, Paolo Domenici, Mark I. McCormick, Christina Sorensen, Sue-Ann Watson, and Philip L. Munday. 2012. "Near-future carbon dioxide levels alter fish behaviour by interfering with neurotransmitter function." *Nature Climate Change* 2 (3) (March): 201–204. doi:10.1038/NCLIMATE1352.
- NOAA PMEL Carbon Program. "OA Observations and Data." <http://www.pmel.noaa.gov/co2/story/OA+Observations+and+Data>.
- Orr, James C. 2011. "Recent and Future Changes in Ocean Carbonate Chemistry." In *Ocean Acidification*, ed. Jean-Pierre Gattuso and Lina Hansson, 41–66. Oxford, UK: Oxford University Press.
- Parker, L. M., Pauline M. Ross, and Wayne A. O'Connor. 2011. "Populations of the Sydney rock oyster, *Saccostrea glomerata*, vary in response to ocean acidification." *Marine Biology* 158 (3) (March): 689–697. doi:10.1007/s00227-010-1592-4.
- Petit, J. R., J. Jouzel, D. Raynaud, N. I. Barkov, J.-M. Barnola, I. Basile, M. Bender, et al. 1999. "Climate and Atmospheric History of the Past 420,000 Years from the Vostok Ice Core, Antarctica." *Nature* 399 (6735) (June 3): 429–436. doi:10.1038/20859.

- Le Quere, Corinne, Michael R. Raupach, Josep G. Canadell, Gregg Marland, Laurent Bopp, Philippe Ciais, Thomas J. Conway, et al. 2009. "Trends in the sources and sinks of carbon dioxide." *Nature Geoscience* 2 (12) (December): 831–836. doi:10.1038/ngeo689.
- Rau, Greg H. 2008. "Electrochemical Splitting of Calcium Carbonate to Increase Solution Alkalinity: Implications for Mitigation of Carbon Dioxide and Ocean Acidity." *Environmental Science & Technology* 42 (23) (December 1): 8935–8940. doi:10.1021/es800366q.
- Rau, Greg H., Elizabeth L. McLeod, and Ove Hoegh-Guldberg. 2012. "The Need for New Ocean Conservation Strategies in a High-carbon Dioxide World." *Nature Climate Change* 2 (10): 720–724. doi:10.1038/nclimate1555.
- Ridgwell, A., and R. E. Zeebe. 2005. "The role of the global carbonate cycle in the regulation and evolution of the Earth system." *Earth and Planetary Science Letters* 234 (3-4) (June 15): 299–315. doi:10.1016/j.epsl.2005.03.006.
- Ries, Justin B, Anne L Cohen, and Daniel C McCorkle. 2009. "Marine Calcifiers Exhibit Mixed Responses to CO<sub>2</sub>-induced Ocean Acidification." *GEOLOGY* 37 (12) (December): 1131–1134. doi:10.1130/G30210A.1.
- Sabine, Christopher L., and Richard A. Feely. 2007. "The Oceanic Sink for Carbon Dioxide." In *Greenhouse Gas Sinks*, ed. D. Reay, N. Hewitt, J. Grace, and K. Smith, 31–49. Edinburgh, UK: University of Edinburgh.
- Sabine, Christopher L., Richard A. Feely, Nicolas Gruber, Robert M. Key, Kitack Lee, John L. Bullister, Rik Wanninkhof, et al. 2004. "The Oceanic Sink for Anthropogenic CO<sub>2</sub>." *Science* 305 (5682) (July 16): 367–371. doi:10.1126/science.1097403.
- Talmage, Stephanie C., and Christopher J. Gobler. 2010. "Effects of Past, Present, and Future Ocean Carbon Dioxide Concentrations on the Growth and Survival of Larval Shellfish." *Proceedings of the National Academy of Sciences*. doi:10.1073/pnas.0913804107. <http://www.pnas.org/content/early/2010/09/17/0913804107.abstract>.
- U.S. Energy Information Administration. 2009. *Emissions of Greenhouse Gases in the United States 2008*. Office of Integrated Analysis and Forecasting, U.S. Department of Energy. <http://205.254.135.7/oiaf/1605/ggrpt/carbon.html>.
- United Nations. 1992a. "The Convention on Biological Diversity." <http://www.cbd.int/convention/text/>.
- . 1992b. "United Nations Framework Convention on Climate Change." [http://unfccc.int/essential\\_background/convention/background/items/1349.php](http://unfccc.int/essential_background/convention/background/items/1349.php).
- . 2002a. "Johannesburg Declaration on Sustainable Development." [http://www.un.org/esa/sustdev/documents/WSSD\\_POI\\_PD/English/POI\\_PD.htm](http://www.un.org/esa/sustdev/documents/WSSD_POI_PD/English/POI_PD.htm).
- . 2002b. "United Nations Millennium Development Goals." <http://www.un.org/millenniumgoals/reports.shtml>.
- United Nations Conference on the Human Environment. 1972. "Rio Declaration on Environment and Development". United Nations. <http://www.unep.org/Documents.Multilingual/Default.asp?documentid=78&articleid=1163>.
- US Department of Commerce, NOAA. "Trends in Carbon Dioxide." <http://www.esrl.noaa.gov/gmd/ccgg/trends/>.
- World Commission on Environment and Development. 1987. *Report of the World Commission on Environment and Development: Our Common Future*. New York: United Nations. <http://www.un-documents.net/wced-ocf.htm>.

Accepted version: See Ocean Yearbook Vol. 27 (2013) for final published version.

Yamamoto-Kawai, Michiyo, Fiona A. McLaughlin, Eddy C. Carmack, Shigeto Nishino, and Koji Shimada. 2009. "Aragonite Undersaturation in the Arctic Ocean: Effects of Ocean Acidification and Sea Ice Melt." *Science* 326 (5956) (November 20): 1098–1100. doi:10.1126/science.1174190.

**Figure captions:**

Figure 1: 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 (Asilomar Scientific Organizing Committee 2010). CCS stands for carbon capture and sequestration.

Figure 1:

