The Journal of Science Policy & Governance

POLICY ANALYSIS:

ADAPTIVE POLICY APPROACHES TO OCEAN ACIDFICATION

Aaron Ray, Georgetown University
aarondray@gmail.com

Executive Summary

Unlike atmospheric climate change forecasts that involve significant uncertainties, ocean acidification is considered a predictable response to increasing atmospheric CO_2 concentrations (Doney, Fabry, Feely, & Kleypas, 2009). Atmospheric CO_2 concentrations are expected to reach 467-555 ppm by Year 2050 (Cooley et al., 2009). Increases of this kind would cause surface ocean pH to decline, on average, to 7.8 in Year 2050 (Cooley et al., 2009). Models of future CO_2 emissions and ocean uptake suggest that the atmospheric level of CO_2 would peak shortly after the highest rate of fossil fuel combustion and then subside as the oceans absorb the CO_2, resulting in increased acidification (Ruttimann, 2006).

Ocean acidification will have complex effects on marine organisms. One predicted effect is a reduction in the calcification rate of some species. Coastal marine estuary ecosystems are highly biologically productive yet are more sensitive to changes in pH than is the open ocean due to their shallower depth, lower salinity, and lower alkalinity (Miller et al., 2009). Mollusks like mussels and oysters, which support valuable marine fisheries, may be especially vulnerable to acidification, resulting in economic losses and social disruptions in societies that depend on marine calcifiers (Cooley & Doney, 2009). Changes in fishery industries due to acidification are likely to disproportionately affect developing nations that often rely more on marine-related economic activities than developed nations (Cooley et al., 2009). Projected revenue losses from mollusk harvest declines due to acidification range from \$0.6-2.6 billion through 2060 (Cooley & Doney, 2009). In addition, projections of lost coral reef area in Year 2100 due to acidification range from 16% to 27% and translate to economic losses of as much as \$870 billion in Year 2100 (Brander et al., 2009).

In the absence of significant reductions in emissions, acidification will continue, requiring adaptation based measures. While mitigation involves a global commitment, adaptation actions can be adopted at the local, national, and international levels. Policies to limit marine pollution and curtail overfishing may have a positive effect on the ability of marine ecosystems to adapt to acidifying conditions (Cooley et al., 2009). Policy instruments to reduce pressure on fisheries include license or vessel buyouts and regional fishery closures (Cooley et al., 2009). Other strategies include increasing aquaculture operations in order to compensate for losses in wild harvests. Adaptation measures to support fishing dependent communities include diverting fishing effort to new or underutilized species, protecting key functional groups, investing in monitoring and research, and decoupling the local economy from fishing (MacNeil et al., 2010). Transfer schemes to compensate developing nations particularly affected by acidification include the Adaptation Fund which supports adaptation activities in developing countries with Clean Development Mechanism (CDM) funding from developed countries. However, with the expiration of the Kyoto Protocol in 2012, there is uncertainty about the future of the Adaptation Fund. As acidification continues, governments will face increased pressure to adopt adaptive policy instruments at the local, national, and international levels.

Introduction

The transfer of anthropogenic CO_2 from the atmosphere to the oceans has and will continue to result in ocean acidification. Impacts of acidification on marine organisms include changes in rates of calcification, photosynthesis, and nitrogen fixation. Acidification may also affect trophic relationships within ecosystems. The effects of acidification are likely to impact economically and socially valuable marine resources and ecosystem services. Potential negative impacts include reduced fisheries harvests, compromised coastal protection, and lost tourism revenue. Adaptive policy responses to acidification include limiting the vulnerability of marine ecosystems, expanding freshwater aquaculture operations, and supporting communities and nations facing economic disruption.

Ocean Acidification

The anthropogenic combustion of fossil fuels and changes in land use driven by industrialization and population growth have resulted in a 38% increase in atmospheric carbon dioxide (CO_2) concentrations from pre-industrial levels (Feely et al., 2004; Orr et al., 2005). The concomitant uptake of anthropogenic CO_2 by the oceans has caused an increase in aqueous CO_2 and decreases in pH, carbonate ion (CO_3^{2-}) concentrations, and the saturation states of calcite (Ω_{ca}) and aragonite (Ω_{ar}) (Cooley, Kite-Powel & Doney, 2009). In addition to the acidifying effect of CO_2 emissions, fossil fuel combustion results in the deposition of compounds of sulfur (H_2SO_4) and nitrogen (HNO_3) in coastal oceans, contributing to acidification (Hester, Peltzer, Kirkwood & Brewer, 2008).

Unlike atmospheric climate change forecasts that involve significant uncertainties, acidification is considered a predictable response to increasing atmospheric CO_2 concentrations (Doney, Fabry, Feely, & Kleypas, 2009). The ocean has absorbed about one-third of anthropogenic CO_2 (or 430 billion tons) from the atmosphere since industrialization (Makarow, Ceulemans, & Horn, 2009). In 1800, the atmosphere contained 280 parts per million (ppm) CO_2 and the ocean pH averaged 8.16 (Ruttimann, 2006). Measures of ocean acidity indicate a decrease in pH to 8.1 in 2009 when the atmospheric CO_2 concentration reached 387 ppm. (Ruttimann, 2006; NOAA, 2011a). In addition, multiple time series measurements have found a drop in average ocean pH of 0.02 within the last decade (Makarow et al., 2009).

Projected Acidification

Atmospheric CO_2 concentrations are expected to reach 467-555 ppm by Year 2050 (Cooley et al., 2009). Increases of this kind would cause surface ocean pH to decline, on average, to 7.8 in Year 2050 (Cooley et al., 2009). A decrease in mean surface Ω_{ca} and Ω_{ar} of 25% relative to 2009 is also likely (Cooley et al., 2009).

Given the acidifying effect of increased sulfur and nitrogen deposition, projections of future ocean pH based solely on CO_2 emissions underestimate the true level of acidification (Hester et al., 2008). Although inputs of these other compounds are responsible for only a small fraction of acidification relative to CO_2 emissions, their deposition and effects are concentrated in coastal waters where ecosystem responses will have a greater impact on human society (Doney et al., 2009).

Long-term projections of continued CO_2 emissions in line with current trends forecast atmospheric CO_2 levels of over 800 ppm by Year 2100 leading to oceans 150% more acidic than they were prior to industrialization (Makarow et al., 2009). Models of future CO_2 emissions and ocean uptake suggest that the atmospheric level of CO_2 would peak shortly after the highest rate of fossil fuel combustion and then subside as the oceans absorb the CO_2, resulting in increased acidification (Ruttimann, 2006). With an emissions peak in Year 2100, the surface pH of the ocean would not begin to stabilize until Year 2750 (Ruttimann, 2006). The pH level a kilometer below the surface, in this scenario, is projected to continue to fall until Year 3000 (Ruttimann, 2006). A general circulation model, simulating an atmospheric CO_2 concentration of 1,900 ppm in Year 2300, projects a maximum reduction in surface pH of 0.77 units (Caldeira & Wickett, 2003).

Although the geological record shows that episodes of acidification occurred in the past and that marine organisms adapted to the increased acidity, past examples of acidification occurred over tens of thousands of years (Erba, Bottini, Weissert & Keller, 2010). Isotope studies of sediments indicate that the current observed and projected rates of acidification are as much as 100 times faster than what occurred in the past (Ruttimann, 2006). Furthermore, reviews of the geological record have found that over the past 300 million years, ocean pH was not more than 0.6 units lower than today (Caldeira & Wickett, 2003). The general circulation model referenced above projects a 0.7 unit decrease in pH due to continued emissions (Caldeira & Wickett, 2003). In light of these projections, continued acidification will present a challenge to marine organisms adapted to current oceanic conditions.

Organism and Ecosystem Impacts

Ocean acidification will have complex effects on marine organisms. One predicted effect is a reduction in the calcification rate of some species. Studies demonstrate that calcification rates of mollusks, corals, and echinoderms decline as CO_3^{2-} ion concentrations in seawater decline (Cooley et al., 2009). Core samples from coral colonies of the Great Barrier Reef showed a decrease in calcification rates of 21% between 1988 and 2003, partly due to a decline in Ω_{ar} (Doney et al., 2009). The mass and calcification of planktonic lobster larvae carapaces has been shown to decline and reproduction of mollusks and echinoderms are negatively affected by increased CO_2 concentrations in seawater (Arnold, Findlay, Spicer, Daniels, & Boothroyd, 2009; Doney et al., 2009). In addition to decreased calcification rates among corals, dissolution rates are expected to increase, especially for reefs near the limit for reef growth (Doney et al., 2009).

Some species may, in fact, benefit from acidification. Planktonic organisms may see increased photosynthesis due to acidification (Cooley & Doney, 2009). Rates of photosynthesis and nitrogen fixation of some coccolithophores, prokaryotes, and cyanobacteria either remain unchanged or rise due to higher concentrations of CO_2 in seawater (Doney et al., 2009). Specifically, an increase in dissolved CO_2 concentrations has been shown to increase light-saturated photosynthetic rates among sea grasses (Doney et al., 2009). It is unclear however whether these gains can compensate for the expected detrimental impacts of acidification.

Acidification also has ecosystem level consequences for organism life cycles and trophic relationships. The development of calcified structures can be stunted or delayed in the planktonic larvae of mollusks and corals, potentially increasing mortality from predation or depleting growth, metamorphosis, and reproduction (Cooley et al., 2009). Other research has found that acidic water affects the respiration rate of squid, negatively impacting their ability to swim (Ruttimann, 2006). In addition to potential impacts on lifecycles, trophic relationships may be affected by acidification. Lower pH has been found to negatively impact survival and development of the calcified Atlantic Ocean brittlestar, a keystone predator (Dupont, Havenhand, Thorndyke, Peck & Thorndyke, 2008). Removal or reduction of keystone predators can cause trophic cascades with unpredictable consequences. Biogeographic shifts in calcifying prey species, namely coccolithophpores and mollusk and coral larvae, have also been documented (Cooley et al., 2009).

Observed ecosystem responses to decreasing pH have been noted. A 0.4 unit decline in pH over eight years in a coastal lagoon was associated with a 10-40% decrease in the population of calcifying organisms (Wootton et. al., 2008). At the same time, macroalgae and seagrasses became dominant (Cooley et al., 2009). This is likely due to the higher rates of photosynthesis noted above and has implications for habitat transformation (Doney et al., 2009). Coastal marine estuary ecosystems are highly biologically productive and provide significant measurable ecosystem services, including support for commercial and recreational fisheries, nursery grounds for fish and invertebrate species, water purification, flood and storm surge protection, and human recreation (Miller et. al.,, 2009). These ecosystems are more sensitive to changes in pH than is the open ocean due to their shallower depth, lower salinity, and lower alkalinity (Miller et al., 2009). Mollusks like mussels and oysters, which support valuable marine fisheries, may be especially vulnerable to acidification, resulting in economic losses and social disruptions in societies that depend on marine calcifiers (Cooley & Doney, 2009). In fact, bivalve larvae are more vulnerable to acidification than adult organisms (Miller et al., 2009). Reports of difficultly keeping Pacific oyster larvae alive in commercial oyster hatcheries in the acidifying waters of the Pacific Northwest suggest the need for more investigation into the possible effects of acidification on commercially important bivalve species (Miller et al., 2009).

The impact of acidification on marine ecosystems will be varied and produce both biological winners and losers (Doney et al., 2009). However, acidification could disrupt the human economic relationship with the oceans that is predicated on the current state of affairs. Changes to this relationship would cause economic and social dislocation that should be addressed by policy makers.

Economic and Social Effects

Marine and coastal pollution, invasive species, coastal deforestation, and overfishing may combine with acidification to result in more fragile and vulnerable marine ecosystems (Makarow et al., 2009). In addition to these other stressors, acidification is likely to affect organisms that support subsistence, commercial, and recreational fisheries, thereby impacting the ability of those ecosystems to provide services upon which humans have come to depend (Cooley et al., 2009). Ecosystem services are the benefits to society provided by marine resources. These services can be divided into four categories: provisioning, regulation, culture, and support (UNEP, *Marine and Coastal Ecosystems,* 2006). Further ocean acidification is expected to impact the ability of ecosystems to provide services in each of these categories. Those services facing acute threats include wild fisheries, aquaculture projects, coastal protection, tourism, cultural identities, and ecosystem support (Cooley et al., 2009).

The global marine capture fisheries and aquaculture industries provided 110 million metric tons of human food in 2006 with a commercial value of $170 billion (FAO, 2009). The value of global fisheries associated with coral reefs alone is estimated to be $5.7 billion per year (Conservation International, 2008). Changes in these industries due to acidification are likely to disproportionately affect developing nations that often rely more on marine-related economic activities than developed nations (Cooley et al., 2009). Projections of population increases and acidification rates suggest that by 2050, low-latitude regions will be most affected, increasing stress on tropical marine ecosystems and the nations that rely upon those ecosystems (Cooley et al., 2009). The total economic value generated by fisheries, including wild fish and aquaculture, is estimated to be $150 billion per year (Makarow et al., 2009). The economic impacts of acidification can be assessed using a Total Economic Value framework, which includes direct and indirect use and non-use values of the damaged resources (Makarow et al., 2009).

Economic Effects

One direct impact of acidification on humans may be a decline in harvest and fishery revenues from shellfish, their predators, and coral reef habitats (Cooley & Doney, 2009). In 2007, the entire U.S. domestic commercial fish harvest was valued at $3.8 billion and contributed $34 billion to U.S. gross national product (Cooley & Doney, 2009). Approximately 24% of that revenue was from fish that prey directly on calcifiers (Cooley & Doney, 2009). Of the total U.S. catch, 19% by weight was made up of mollusks (Cooley & Doney, 2009). Recreational fishing also creates economic benefits with expenditures on services, equipment, and travel. In 2000, recreational saltwater fishing produced $12 billion in income, supported 350,000 jobs, and generated a total economic benefit of $43 billion in the U.S. (Cooley et al., 2009). If acidification damages marine habitats or reduces harvests, the resulting decline in revenues could produce job losses and additional indirect economic costs (Cooley & Doney, 2009).

A 0.1-0.2 unit decrease in pH is expected to result in mollusk harvest declines of 6-25% over 50 years (Cooley & Doney, 2009). With a moderate net discount rate of 2%, the net present value of revenue losses from mollusk harvest declines due to acidification would range from $0.6-2.6 billion through 2060 (Cooley & Doney, 2009). Importantly, these loses would be four times higher in New England, with a highly mollusk dependent fishery, than in the Pacific (Cooley & Doney, 2009). These are direct economic losses only. The secondary economic effects and socio-economic dislocations are expected to be even larger.

National data on the number of jobs supported by fishing is incomplete. However, commercial fish processing and wholesaling alone supported 63,000 U.S. jobs in 2007 (Cooley & Doney, 2009). In the state of New York commercial fishing employed 10,500 people, processing and wholesaling supported 5,060 jobs, and retail fish sales supported 10,000 jobs in 1999 (Cooley & Doney, 2009). In addition, seafood sales at New York restaurants supported the equivalent of 70,000 full-time jobs (Cooley & Doney, 2009). In sum, the fishing industry supported almost 100,000 jobs in the state (Cooley & Doney, 2009). Scaling these figures up to the national or international level suggests the scope of the challenge acidification presents if harvests decline.

Impacts on Reefs

In addition to the effect on fisheries, acidification will likely impact coral reefs and the economic activities they support. Coral reefs function as habitat for commercial fish stocks, barriers protecting coastlines, and catalysts for recreation and tourism (Makarow et al., 2009). The value of coral reefs include direct use values such as coral mining and recreational opportunities, as well as indirect use values including the impact on real estate prices, coastal protection, and habitat and nursery functions for commercial and recreational fisheries (Brander, Rehdanz, Tol, & van Beukering, 2009). In addition, there is the welfare value of preserving a diverse natural ecosystem (Brander et al., 2009). The global economic value of these reef services has been estimated to be $30 billion per year based on a value of $100,000 per square kilometer per year (Cooley et al., 2009). Given their open access nature and role as a public good, reefs are usually undervalued in decisions that relate to their use and conservation (Brander et al., 2009).

The global economic value of just the shoreline protection provided by coral reefs is estimated to be $9 billion per year (Cesar, Burke & Pet-Soede, 2003). If reefs, which buffer coastlines from storm waves and tsunamis, are compromised by acidification, the ecosystem services of coastline protection and shoreline stabilization would be lost (Cooley et al., 2009). This would result in greater economic losses from storms and require greater investment in seawalls and other fortifications to protect property (Cooley et al., 2009). Recent estimates found that projected damage to coral reefs due to acidification would result in a 0.18% loss in global gross domestic product in Year 2100 (Makarow et al., 2009). In 2000, the total area of coral reefs globally was 307,000 km^2 (Brander et al., 2009). Projections of lost coral reef area in Year 2100 due to acidification only, excluding degradation due to warming, sea level rise, and other pollution, range from 16% (30,000 km^2) to 27% (65,000 km^2) (Brander et al., 2009). These projected losses in coral reef area translate to economic losses of as much as $870 billion in Year 2100 (Brander et al., 2009).

Distributional Impacts

The economic impacts of acidification will also have distributional implications. Internationally, fish provides more than 20% of the dietary protein for 2.6 billion people, mostly in developing countries (Makarow et al., 2009). The Atlantic and Pacific fisheries are heavily dependent on acidification-vulnerable organisms, such as mollusks and crustaceans (Cooley et al., 2009). In addition, coral reefs are primarily located in and provide ecosystem services to developing nations (Makarow et al., 2009). Developing countries in the Pacific rely on calcifying species such as mollusks and corals for 20% of their catch (Cooley et al., 2009). Many of these small island nations have few economic alternatives to fishing to supply both income and protein (Cooley et al., 2009).

In 2006, global marine capture fisheries and aquaculture produced 13.6 kg per capita of seafood (FAO, 2009). As standards of living have risen, aquaculture has allowed global seafood production to keep up with increasing demand for protein. While capture harvests declined from 12.5 kg per capita in the 1980s to 10 kg per capita in 2006, aquaculture harvests filled the gap (FAO, 2009). Global mollusk aquaculture has grown 7.7% per year since 1970 and today provides 14 million metric tons of food valued at $10 billion per year (Cooley et al., 2009). Understanding the implications of acidification on global seafood consumption and income security begins with recognizing that the consumption of protein from seafood is unevenly distributed worldwide. In developing countries such as Bangladesh, Cambodia, Gambia, Ghana, Indonesia, and others, seafood provides more than 50% of dietary protein (FAO, 2009).

Adaptive Policy Approaches

Policy makers considering ways to address acidification have a menu of options. The most obvious, and thus far most politically difficult, is to reduce CO_2 emissions in order to avoid the most severe impacts of acidification. Past emissions CO_2 in the atmosphere will continue to contribute to future acidification. While limiting the extent of acidification depends upon curtailing future emissions, efforts at mitigation have thus far been unsuccessful. The lack of comprehensive policies to reduce emissions in the U.S. and other nations with significant emissions, as well as the inability of the international community to adopt binding reduction targets to replace the expiring Kyoto Protocol, make meaningful emissions reductions in the near term unlikely.

In the absence of significant reductions in emissions, acidification will continue, requiring adaptation based measures. While mitigation will require a global commitment, adaptation actions can be adopted at the local, national, and international levels. In the U.S., the White House's Interagency Climate Change Adaptation Task Force defines adaptation as "an adjustment in natural of human systems in response to actual or expected climatic stimuli or their effects" (CEQ, 2010a). In order to further adaptation efforts in the U.S., the Ocean Policy Task Force, coordinated by the White House Council on Environmental Quality, made strengthening the ability of coastal communities and marine environments to adapt to acidification a national priority (CEQ, 2010b).

National Policies

One set of adaptation strategies focuses on limiting the vulnerability of ecosystems to the stresses of acidification. Therefore, policies to limit marine pollution and curtail overfishing may have a positive effect on the ability of marine ecosystems to adapt to acidifying conditions (Cooley et al., 2009). Reducing harvest limits in the near term may result in short term revenue losses, but larger fish stocks and higher revenues in the long term (Cooley et al., 2009). Policy instruments to reduce pressure on fisheries include license or vessel buyouts and regional fishery closures (Cooley et al., 2009). Other strategies include increasing aquaculture operations in order to compensate for losses in wild harvests. In acidifying seas, aquaculture operations may have to use selective breeding techniques to rear species able to withstand these conditions (Cooley et al., 2009). In addition, freshwater aquaculture operations, isolated from acidifying oceans, may become more attractive as a means of supplying protein to consumers.

Within nations, extractive users, such as fishermen and aquaculture operators, face additional costs and economic losses if harvests decline (Cooley et al., 2009). A number of adaptation measures are available to support fishing dependent communities. Possible actions include diverting fishing effort to new or underutilized species, protecting key functional groups, investing in monitoring and research, and decoupling the local economy from fishing (MacNeil et al., 2010). This last action entails the greatest disruption to existing economic and social structures. Therefore, the social costs of lost employment and dislocation may require subsidies from less affected segments of the national population. Social policies such as job retraining and relocation assistance may be required to support formerly fishery-dependent communities (Cooley et al., 2009). For example, the U.S. National Oceanic and Atmospheric Administration (NOAA) requested $8 million to create a National Working Waterfronts grant program to aid fishing-dependent communities diversify their economies (NOAA, 2011b).

International Adaptation

The international distributional challenges of acidification are significant. Developed nations are responsible for the largest portion of historic emissions and therefore for current acidification. They also possess the most diverse economies and food systems. Transfer schemes to compensate developing nations particularly affected by acidification may be warranted. Mechanisms to achieve this include the Adaptation Fund, established by the parties to the Kyoto Protocol (UNFCCC, 2010a). The Fund supports adaptation activities in developing countries with Clean Development Mechanism (CDM) funding from developed countries. However, with the expiration of the Kyoto Protocol in 2012, there is uncertainty about the future of the CDM and hence, the Adaptation Fund. The Copenhagen Accord, agreed to by 114 parties in 2009, recommitted developed countries to providing financial resources to support adaptation measures in developing countries (UNFCC, 2010b). Unfortunately, the Obama administration's proposed funding for international adaptation aid has not found support in the current U.S. Congress (Friedman, 2011). This lack of support by the U.S. may deter other nations from meeting their commitments. However, if the impacts of acidification in developing nations intensify, developed nations may face increased pressure to meet these commitments.

Ocean acidification is an unambiguous consequence of increasing atmospheric CO_2 concentrations. While reducing CO_2 emissions will be necessary to limit the most disruptive effects, the process of acidification has begun and will continue in the future. Policy instruments are available to reduce the vulnerability of marine ecosystems and coastal communities to changes in the composition and productivity of the oceans' biological systems. Given the economic and social importance of the oceans to human societies, governments at the local, national, and international levels must begin to assess and implement adaptive approaches to acidification.

References

Arnold, K.E., H.S. Findlay, J.I. Spicer, C.L. Daniels, and D. Boothroyd. 2009. Effect of CO2-related acidification on aspects of the larval development of the European lobster, *Homarus gammarus* (L.).*Biogeosciences.* 6:1,747–1,754.

Brander, L.M., Rehdanz, K., Tol, R.S., van Beukering, P.J., 2009. The Economic Impact of Ocean Acidification on Coral Reefs. *Economic and Social Research Institute*. Working Paper No. 282. Accessed 10/15/10 from: http://www.esri.ie/UserFiles/publications/20090218113337/WP282.pdf

Caldeira, K., Wickett, M., 2003. Anthropogenic carbon and ocean pH. *Nature*. 425, 365.

Cesar, H.J.S., Burke, L., and Pet-Soede, L. , 2003. *The Economics of Worldwide Coral Reef Degradation.* Cesar Environmental Economics Consulting, Arnhem, and WWF-Netherlands, Zeist, The Netherlands. Accessed 3/16/11 from: http://assets.panda.org/downloads/cesardegradationreport100203.pdf

CEQ, 2010a. *Progress Report of the Interagency Climate Change Adaptation Task Force: Recommended Actions in Support of a National Climate Change Adaptation Strategy*. The White House Council on Environmental Quality. Accessed 10/15/10 from: http://www.whitehouse.gov/sites/default/files/microsites/ceq/Interagency-Climate-Change-Adaptation-Progress-Report.pdf

CEQ, 2010b. *Final Recommendations of the Interagency Ocean Policy Task Force*. The White House Council on Environmental Quality. Accessed 10/13/10 from: http://www.whitehouse.gov/files/documents/OPTF_FinalRecs.pdf

Conservation International, 2008. *Economic Values of Coral Reefs, Mangroves, and Seagrasses: A Global Compilation.* Conservation International, Arlington, VA, USA, 23 pp.

Cooley, S.R., Doney, S.C., 2009. Anticipating ocean acidification's economic consequences for commercial fisheries. *Environmental Research Letters*. 4, 024007.

Cooley, S.R., Kite-Powel, H.L., Doney, S.C., 2009. Ocean Acidification's Potential to Alter Global Marine Ecosystem Services. *Oceanography* 22:4, 172-181.

Doney, S.C., Fabry, V.J., Feely, R.A., Kleypas, J.A., 2009. Ocean Acidification: The Other CO2 Problem. *Annual Review of Marine Science*. 1:169–92.

Dupont, S., J. Havenhand, W. Thorndyke, L. Peck, and M. Thorndyke, 2008. Near-future level of CO2-driven ocean acidification radically affects larval survival and development in the brittlestar *Ophiothrix fragilis*. *Marine Ecology Progress Series* 373:285–294.

Erba, E., Bottini, C., Weissert, H.J., Keller, C.E., 2010. Calcareous Nanoplankton Response to Surface-Water Acidification Around Oceanic Anoxic Event 1a. *Science.* 329, 428-432.

FAO, 2009. *The State of Fisheries and Aquaculture 2008*. Food and Agriculture Organization of the United Nations, Rome, Italy, 196 pp.

Feely, R.A., C.L. Sabine, L. Kitack, W. Berelson, J. Kleypas, V.J. Fabry, and F.J. Millero, 2004. Impact of anthropogenic CO2 on the CaCO3 system in the oceans. *Science* 305:362–366.

Friedman, L., 2011. Deep cuts in proposed U.S. climate aid to developing nations may not be restored. *ClimateWire*. Accessed 3/16/11 from: http://www.eenews.net/climatewire/2011/03/02/archive/4?terms=adaptation

Hester, K.C., Peltzer, E.T., Kirkwood, W.J., Brewer, P.G., 2008. Unanticipated consequences of ocean acidification: A noisier ocean at lower pH. *Geophysical Research Letters* 35:L19601.

House, K.Z., House, C.H., Schrag, D.P., Aziz, M.J., 2007. Electrochemical Acceleration of Chemical Weathering as an Energetically Feasible Approach to Mitigating Anthropogenic Climate Change. *Environmental Science & Technology*. 41, 8464–8470.

MacNeil, M.A., Graham, N.A., Cinner, J.E., Dulvy, N.K., Loring, P.A., Jennings, S., Polunin, N.V., Fisk, A.T., McClanahan, T.R., 2010. Transitional states in marine fisheries: adapting to predicted global change. *Philosophical Transactions of The Royal Society*. 365, 3753–3763.

Makarow, M., Ceulemans, R., Horn, L., 2009. Science Policy Briefing: Impacts of Ocean Acidification. *European Science Foundation*. Accessed 10/15/10 from: http://www.solas-int.org/resources/ESF__Impacts-OA.pdf

Miller, A.W., Reynolds, A.C., Sobrino, C., Riedel, G.F., 2009. Shellfish Face Uncertain Future in High CO2 World: Influence of Acidification on Oyster Larvae Calcification and Growth in Estuaries. *PLoS ONE*. 4:5, e5661.

NOAA, 2011a. Mauna Loa CO2 annual mean data. National Oceanic and Atmospheric Administration. Accessed 04/10/2011 from: ftp://ftp.cmdl.noaa.gov/ccg/co2/trends/co2_annmean_mlo.txt

NOAA, 2011b. *Fiscal Year 2012 Blue Book*. National Oceanic and Atmospheric Administration. Accessed 3/16/11 from: http://www.corporateservices.noaa.gov/nbo/fy12_bluebook/chapter1_2012_BudgetHighlights.pdf

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, and others. 2005. Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms. *Nature.* 437:681–686.

Ruttimann, J., 2006. Sick Seas. *Nature*. 442:31, 978-980.

UNEP. 2006. *Marine and Coastal Ecosystems and Human Wellbeing: A Synthesis Report Based on the Findings of the Millennium Ecosystem Assessment.* United Nations Environment Programme. P. 76.

UNFCCC, 2010a. *Adaptation Fund*. United Nations Framework Convention on Climate Change. Accessed 3/16/11 from: http://unfccc.int/cooperation_and_support/financial_mechanism/adaptation_fund/items/3659.php

UNFCCC, 2010b. *Copenhagen Accord*. United Nations Framework Convention on Climate Change. Accessed 3/16/11 from: http://unfccc.int/resource/docs/2009/cop15/eng/11a01.pdf

Wootton, J.T., C.A. Pfister, and J.D. Forester. 2008. Dynamic patterns and ecological impacts of declining ocean pH in a high-resolution multi-year dataset. *Proceedings of the National Academy of Sciences of the United States of America.* 105(48):18,848–18,853.

About the Author

Aaron Ray earned an M.P.P. at the Georgetown Public Policy Institute in 2011 with a specialization in Environmental and Regulatory Policy. He also earned an M.A. in Education from the University of New Mexico and a B.A. in Philosophy, Political Science, and Religion from Linfield College. He has worked on environmental issues at the Council on Environmental Quality, the Climate Institute, and the Pew Research Center. His research and policy interests include climate change policy, municipal environmental initiatives, and transportation and energy policy.