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Ocean Acidification

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Summary

With increasing concentrations of carbon dioxide (CO_2) in the atmosphere, the extent of effects on the ocean and marine resources is an increasing concern. One aspect of this issue is the ongoing process (known as ocean acidification) whereby seawater becomes less alkaline as more CO_2 dissolves in it, causing hydrogen ion concentration in seawater to increase. Scientists are concerned that increasing hydrogen ion concentration could reduce growth or even cause death of shell-forming animals (e.g., corals, mollusks, and certain planktonic organisms) as well as disrupt marine food webs and the reproductive physiology of certain species. While not yet fully understood, the ecological and economic consequences of ocean acidification could be substantial.

Scientists are concerned that increasing hydrogen ion concentration in seawater could alter biogeochemical cycles, disrupt physiological processes of marine organisms, and damage marine ecosystems. This report does not discuss the effects of increasing thermal stress to marine organisms and ecosystems (e.g., coral bleaching) related to climate change. However, marine ecosystems are likely to be affected by the synergistic effects of factors involved in both thermal and chemical processes.

Congress is beginning to focus attention on better understanding ocean acidification and determining how this concern might be addressed. In the 111th Congress, the Federal Ocean Acidification Research and Monitoring Act of 2009 (Title XII, Subtitle D, of P.L. 111-11) directed the Secretary of Commerce to establish an ocean acidification program within NOAA, established an interagency committee to develop an ocean acidification research and monitoring plan, and authorized appropriations through FY2012 for NOAA and the National Science Foundation. The only bill related to ocean acidification that has been introduced during the 113th Congress is the Coral Reef Conservation Act Amendments of 2013 (S. 839). S. 839 would include ocean acidification in the criteria used to evaluate project proposals for studying threats to coral reefs and developing responses to coral reef losses. On July 30, 2013, the Senate Committee on Commerce, Science and Transportation ordered S. 839 to be reported.

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Introduction

On January 30, 2009, a Monaco Declaration was signed by more than 150 marine scientists from 26 countries, calling for immediate action by policymakers to reduce carbon dioxide emissions so as to avoid widespread and severe damage to marine ecosystems from ocean acidification.[1] The Monaco Declaration is based on the *Research Priorities Report* developed by participants in an October 2008 international symposium on "The Ocean in a High-CO_2 World,"[2] organized by UNESCO's Intergovernmental Oceanographic Commission, the Scientific Committee on Oceanic Research, the International Atomic Energy Agency, and the International Geosphere Biosphere Programme. In December 2010, the United Nations Environment Programme highlighted the emerging concerns over the relationship between ocean acidification and food security.[3] While not yet fully understood, the ecological and economic consequences of ocean acidification could be substantial. Legislative attention by Congress on ocean acidification currently is focused on authorizing, funding, and coordinating research to increase knowledge about ocean acidification and its potential effects on marine ecosystems.

What Is Ocean Acidification?

The complex interplay between rising carbon dioxide (CO_2) levels in the atmosphere and the ocean's chemistry is a process that scientists have recognized for more than a century. As increasing CO_2 from the atmosphere dissolves in seawater, seawater chemistry is altered. The prevailing pH (a measure of hydrogen ion concentration) of water near the ocean surface is around 8.1, or slightly alkaline.[4] Ocean acidification is the name given to the ongoing process whereby pH decreases as seawater becomes less alkaline when increasing amounts of anthropogenic CO_2 from the atmosphere dissolve in seawater. When atmospheric CO_2 dissolves into the ocean, it forms carbonic acid (H_2CO_3). Some of the carbonic acid dissociates in ocean waters, producing hydrogen ions (H^+). As the number of hydrogen ions increases, the pH of the ocean decreases, and the water becomes less alkaline.

Scientists are concerned that this change in seawater pH could alter biogeochemical cycles, disrupt physiological processes of marine organisms, and damage marine ecosystems. This report does not discuss the effects of increasing thermal stress to marine organisms and ecosystems (e.g., coral bleaching) related to climate change. However, marine ecosystems are likely to be affected by the synergistic effects of factors involved in both thermal and chemical processes.

[1] A copy of this declaration is available at http://scrippsnews.ucsd.edu/Releases/doc/MonacoDeclaration.pdf.

[2] The full report is available at http://ioc3.unesco.org/oanet/Symposium2008/ ResearchPrioritiesReport_OceanHighCO2WorldII.pdf.

[3] *UNEP Emerging Issues: Environmental Consequences of Ocean Acidification: A Threat to Food Security*, available at http://www.grid.unep.ch/product/publication/download/Environmental_Consequences_of_Ocean_Acidification.pdf.

[4] The pH scale is an inverse logarithmic representation of hydrogen proton (H+) concentration, indicating the activity of hydrogen ions (or their equivalent) in the solution. A pH of less than 7.0 is considered acidic, while a pH greater than 7.0 is considered basic (alkaline); a pH level of 7.0 is defined as "neutral."

At What Rate Is Ocean Acidification Occurring, and What Factors Affect This Rate?

Over the past several decades, the oceans annually have absorbed about 2 billion metric tons of the approximately 7 billion metric tons of carbon that all the countries in the world release as CO_2 into the atmosphere each year.[5] It has been estimated that a total of more than 530 billion tons of CO_2 have been absorbed by the ocean between 1800 and 1994,[6] with the average pH of water near the ocean surface decreasing by almost 0.1 pH unit.[7] That decrease sounds small, but it represents a 26% increase in the concentration of hydrogen ions, because the pH scale is logarithmic (i.e., water with a pH of 6 is 10 times less acidic than water with a pH of 5, and 100 times less acidic than water with a pH of 4). Open ocean observational records of declining pH are available from the Hawaiian Ocean Time-Series Station in the Pacific and the Bermuda Atlantic Time-Series Station in the Atlantic.[8] Up to a point, as atmospheric CO_2 continues to increase, ocean pH will continue to decrease; one estimate suggests that the rate of CO_2 uptake by the oceans could stabilize at around 5 billion metric tons per year by 2100.[9] One prediction suggests that continued burning of fossil fuels and future uptake of CO_2 by the ocean could reduce ocean pH by 0.3-0.5 units.[10]

All gases, such as CO_2, are less soluble in water as temperature increases. Thus, marine waters near the poles have a much greater capacity for dissolving CO_2 than do ocean waters in the tropics. In addition, dissolved CO_2 is transported into ocean depths at these high latitudes (i.e., deep water formation mechanism) since the lower-temperature waters are of higher density, causing greater convection to occur than happens in the more stratified tropical oceans. If temperature were the only factor affecting the rate of ocean acidification and its impacts on physical and biological features, these impacts might be more likely to occur in marine waters nearer the poles. However, in addition to temperature, other factors modulate the impact of CO_2 on marine waters. Cellular respiration and organic decomposition add CO_2 to seawater, and photosynthesis removes it. Deep oceanic water is enriched in CO_2 due to respiration in the absence of photosynthesis and, when brought to the surface by equatorial currents (i.e., upwelling), can place CO_2-enriched seawater in contact with the atmosphere where it can absorb even more CO_2. Hence, the tropics, and most notably tropical coral reefs, are also vulnerable to near-term effects. An additional factor is the potential increase in storm activity at higher latitudes, as some climate models suggest.[11] CO_2 and other acidic gasses such as nitrogen dioxide

[5] Richard A. Feely, Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration, U.S. Department of Commerce, World Ocean Forum, November 13-14, 2006, at http://www.thew2o.net/events/oceans/oa_q_and_a.php; and Richard A. Feely et al., "Impact of Anthropogenic CO_2 on the $CaCO_3$ System in the Oceans," *Science* (2004), vol. 305, pp. 362-366.

[6] C. L. Sabine, "The Oceanic Sink for Anthropogenic CO_2," *Science*, v. 305 (2004): 367-371.

[7] James C. Orr et al., "Anthropogenic Ocean Acidification over the Twenty-First Century and Its Impact on Calcifying Organisms," *Nature*, vol. 437 (2005): 681-686.

[8] See http://hahana.soest.hawaii.edu/hot/hot_jgofs.html and http://www.bios.edu/research/bats.html.

[9] David Archer, "Fate of Fossil Fuel CO_2 in Geologic Time," *Journal of Geophysical Research*, v. 110 (2005): C09S05, doi:10.1029/2004JC002625.

[10] A. J. Andersson et al., "Coastal Ocean and Carbonate Systems in the High CO_2 World of the Anthropocene," *American Journal of Science*, v. 305 (2005): 875–918.

[11] See the Intergovernmental Panel on Climate Change's *Technical Paper on Climate Change and Water*, available at http://www.ipcc.ch/meetings/session28/executive_summary.pdf.

are also dissolved in rainwater.[12] An increase in North Atlantic or western North Pacific storms could significantly accelerate the pH decrease of surface ocean waters in these regions.

Key scientific questions concern which factors may affect the future rate at which seawater pH might decrease, especially whether the rate of decrease will remain constant in direct relationship to the amount of CO_2 in the atmosphere or whether other factors, such as rising ocean temperatures diminishing CO_2 absorption,[13] will decelerate the rate that pH changes. There is also the question of equilibrium—that is, how long might it take the process whereby the pH of warming ocean waters is decreasing to come into equilibrium with the concentration of atmospheric CO_2, should the currently increasing atmospheric emission rate of CO_2 eventually stabilize or diminish? An adjunct to this question is how long might it take the rate of ocean acidification to slow (or even reverse) in response to increasing water temperatures and any measures that might be taken to slow, halt, or even reverse the increasing concentration of CO_2 in the atmosphere?[14] Additional questions relate to how ocean circulation, which partially controls the CO_2 uptake rate, might change in response to changes in the overlying climate as a result of greenhouse gas emissions.

What Are Some of the Potential Effects of Ocean Acidification?

Since the marine environment is complex and some of the likely changes may be years in the future, the potential effects identified in this section, although many are supported by laboratory experimentation, are primarily conjecture and/or forecasts. However, field studies are beginning to provide a more direct view of potential ocean acidification problems.[15]

Effects of Changing Ocean Chemistry

A lower pH affects marine life in the oceans and is related to other changes in ocean chemistry. In addition to the lower pH, another consequence of the increased amount of dissolved CO_2 in the ocean is the production of more bicarbonate ions (HCO_3^{1-}). As more CO_2 dissolves into the ocean, bicarbonate ions form at the expense of carbonate ions (CO_3^{2-}), which scientists often describe by the following reaction:

$$CO_2 + CO_3^{2-} + H_2O = 2HCO_3^{1-}$$

The abundance and availability of carbonate ions are critical to many shell-forming marine organisms. At current average ocean pH levels (about 8 or above), ocean waters near the surface

[12] Rainwater is naturally acidic at a pH of around 5.6, and downwind of pollution sources has been measured as low as pH 3.0.

[13] Galen A. McKinley et al., "Convergence of Atmospheric and North Atlantic Carbon Dioxide Trends on Multidecadal Timescales," *Nature Geoscience*, v. 4, no. 9 (September 2011): 606-610.

[14] The CO_2 equilibration time between the surface mixed-layer of the ocean and the atmosphere is relatively fast—i.e., less than a year. Thus, the surface waters are anticipated to respond quickly to reductions in atmospheric CO_2. However, equilibration of CO_2 for the entire ocean is more complex as mixing between the surface layer and the deep ocean will take centuries to millennia.

[15] See, for example, K. K. Yates and R. B. Halley, "Diurnal Variations in Rates of Calcification and Carbonate Sediment Dissolution in Florida Bay," *Estuaries and Coasts*, v. 29 (2006): 24-39; and K. K. Yates and R. B. Halley, CO_3^{2-} Concentration and pCO_2 Thresholds for Calcification and Dissolution on the Molokai Reef Flat, Hawaii," *Biogeosciences*, v. 3 (2006): 357-369.

have ample carbonate ions to support shell formation and coral growth. However, as increased amounts of carbonic acid form in the ocean as a result of higher atmospheric CO_2 levels, pH decreases and the amount of carbonate ions in the oceans declines, resulting in fewer carbonate ions available for making shells.

Organisms make biogenic calcium carbonate for their shells and skeletons by combining calcium ions (Ca^{2+})—which are abundant in the oceans—with carbonate ions to form solid calcium carbonate ($CaCO_3$). Certain marine organisms (e.g., corals and pteropods) precipitate one mineral type of calcium carbonate called aragonite, and other marine organisms (e.g., foraminifera and coccolithophorids) use another type called calcite. A third type of calcium carbonate—high magnesium calcite—is precipitated by echinoderms (sea urchins and starfish) and some coralline algae (an encrusting form of red algae that forms calcareous crusts like coral). Under present conditions of ocean chemistry, these forms of calcium carbonate are relatively stable in waters near the ocean surface, except for certain areas of high upwelling activity.[16]

Water near the ocean surface currently is supersaturated (i.e., more concentrated than normally possible and therefore not in equilibrium) with calcite, high magnesium calcite, and aragonite, meaning that organisms easily can form shells from all of these mineral types. However, as more carbonic acid is formed in water near the ocean surface from higher levels of CO_2 in the atmosphere, the level of saturation decreases. If the ocean waters become undersaturated, then shells made from all of these minerals would tend to dissolve. Shells made from high magnesium calcite would tend to dissolve first, at lower concentrations of carbonic acid (and thus at higher pH values) than would shells made from aragonite. Shells made from calcite would dissolve at higher concentrations of carbonic acid than those made from aragonite.[17] Thus, organisms that incorporate high magnesium calcite (i.e., echinoderms and some coralline algae) are likely to be the "first responders" to ocean acidification.[18]

Ocean waters at depths of thousands of feet are undersaturated with respect to all forms of biogenic calcite, which is why most of the shells from dead organisms that "rain" down from the ocean surface dissolve before reaching the ocean floor.[19] Because of the combined effects of increased CO_2 and calcium carbonate solubility in cold water, some suggest that marine surface waters closer to the poles may become undersaturated within the next 50 years.[20] Researchers at the Antarctic Climate and Ecosystems Cooperative Research Centre have demonstrated significant reductions in shell mass and thickness of several Southern Ocean marine algae and animals that appear consistent with the projected effects of recent decreases in seawater pH.[21]

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[16] Results from a 2007 National Oceanic and Atmospheric Administration survey along the U.S. West Coast documented the first undersaturated waters at the ocean surface along the California coast, brought to the surface by seasonal upwelling. See Richard A. Feely et al., "Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf," *Science*, v. 320, no. 5882 (June 13, 2008): 1490-1492.

[17] See Railsback, *Some Fundamentals of Mineralogy and Geochemistry*, at http://www.gly.uga.edu/railsback/Fundamentals/820HMC-LMCSolubilities05LS.pdf.

[18] Andreas J. Andersson, Fred T. Mackenzie, and Nicholas R. Bates, "Life on the Margin: Implications of Ocean Acidification on Mg-Calcite, High Latitude and Cold-Water Marine Calcifiers," *Marine Ecology Progress Series*, v. 373 (2008): 265-273.

[19] Recent research suggests that no more than about 30% of the calcium carbonate produced in the surface ocean each year is buried in shallow or deep sea sediments; the rest dissolves on its way down the water column. See Feely et al. (2004), p. 365.

[20] Orr et al. (2005).

[21] Bruce Mapstone, "Acid Oceans in the Spotlight," *Antarctic Climate and Ecosystem News*, edition 4 (August 2008): 1.

Response of Marine Life to Changing Ocean Chemistry

Although there has been a great deal of work growing organisms under different pHs, most species have biochemical mechanisms to regulate internal pH and are able, within limits, to grow skeletons even when the external medium is less alkaline. A lower pH environment may cause these organisms to expend more energy, but overall they may be able to adapt in complex and species-specific ways. Understanding how marine life might respond to less alkaline conditions is more complicated than the simple claims that all will dissolve, which may ignore the actual physiology of these organisms.

Corals

Some have raised questions downplaying the potential harm to coral reefs from ocean acidification. Differences of opinion exist on the relative effects of climate change as expressed in increased CO_2 when compared to increased ocean temperature. Opinion has been expressed that, in marine systems, increased temperature may have detrimental effects comparable to or larger than those seen from increased CO_2 concentration, for corals and for phytoplankton.[22] Although calcification rates in massive *Porites* coral were reported to have declined over a 16-year study period by approximately 21% in two regions on Australia's Great Barrier Reef, these findings were consistent with other studies of the synergistic effect of elevated seawater temperatures and CO_2 concentrations on coral calcification.[23] Concerns have also been expressed for coral reefs in the eastern tropical Pacific.[24] While ocean acidification may not appear currently to be killing corals, decreasing seawater pH is slowing development of coral larvae into juvenile colonies.[25]

Some project that, in coral reef ecosystems, coral calcification will be reduced by 30% on average by the end of the century.[26] Calcareous algae, another contributor to building the reef frame, will recruit, grow, and calcify under lower pH.[27] However, the dissolution of reef carbonate by boring microflora could increase by 50% under less alkaline conditions by the end of the century.[28] The decrease in coral and crustose coralline algae combined with the increase of carbonate dissolution under less alkaline conditions has the potential to jeopardize the maintenance and resilience of coral reefs and their services to human populations (in terms of food and economic resources).

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[22] Clinton E. Hare et al., "Consequences of Increased Temperature and CO2 for Phytoplankton Community Structure in the Bering Sea," *Marine Ecology Progress Series*, v. 352 (2007), p. 14.

[23] T. F. Cooper et al., "Declining Coral Calcification in Massive *Porites* in Two Nearshore Regions of the Northern Great Barrier Reef," *Global Change Biology*, v. 14 (2008): 529-538.

[24] D. P. Manzello et al., "Poorly Cemented Coral Reefs of the Eastern Tropical Pacific: Possible Insights into Reef Developments in a High-CO_2 World," *Second Symposium on the Ocean in a High-CO_2 World*, Monaco, October 6-9, 2008.

[25] R. Albright et al., "Effect of Aragonite Saturation State on Settlement and Post-Settlement Growth of *Porites astreoide*s Larvae," *Coral Reefs*, v. 27, no. 3 (2008): 485-490.

[26] Joan A. Kleypas et al., "Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs, " *Science*, v. 284, no. 5411 (April 2, 1999): 118-120; C. Langdon and M.J. Atkinson, "Effect of Elevated pCO_2 on Photosynthesis and Calcification of Corals and Interactions with Seasonal Change in Temperature/Irradiance and Nutrient Enrichment," *Journal of Geophysical Research*, v. 110 (2005): C09S07. doi:10.1029/2004JC002576.

[27] I. B. Kuffner et al., "Decreased Abundance of Crustose Coralline Algae due to Ocean Acidification," Nature Geoscience, v. 1, no. 2 (2008): 114-117.

[28] A. Tribollet et al., "Effects of Elevated pCO_2 on Dissolution of Coral Carbonates by Microbial Euendoliths," *Global Biogeochemical Cycles*, doi:10.1029/2008GB003286, in press.

Emerging evidence for the variability in coral response to acidification as well as response to past climate change suggest greater heterogeneity in the pace and degree of reef degradation.[29] In addition, shallow-water coral reefs with long water residence times may be able to mask the effects of ocean acidification in some downstream habitats.[30] In support of the ability of certain corals to survive decreasing pH, stony and soft corals have been grown successfully in open systems with water from a saltwater well at a pH between 7.5 and 7.8 since the 1970s.[31] However, given the high level of adaptation in corals to facilitate calcification via complex processes, at least some corals may be sensitive to changes in pH because of adaptation to invariant pH, with evidence coming primarily from the discovery that periods of high CO_2 in the geological past were often also periods of low aragonite-coral abundances and diversity.[32] Others have found that certain species of coral survive in the laboratory at a pH of 7.3 to 7.6 after their calcified structure dissolves by functioning similar to sea anemones, and retaining the ability to recalcify when pH is increased.[33] However, in the natural marine environment, predation could be a significant factor in limiting the viability of such "naked" corals, and it is unlikely that such organisms could form reefs and attract the diverse community that constitutes a coral reef.

Other Invertebrates

Increasing acidification may alter marine microbial activity, resulting in fundamental changes to how nitrogen is cycled in the ocean. Ocean acidification appears to decrease nitrification, which could reduce emissions of the greenhouse gas nitrous oxide to the atmosphere. In addition, an unknown but potentially significant proportion of the ocean's primary productivity could shift from nitrate- to ammonium-supported, possibly resulting in cascading effects in marine food webs.[34]

In the open ocean, some species of phytoplankton (i.e., microscopic floating plant life) may respond positively (increasing their primary production rate) to rising CO_2 concentrations in the ocean, while others, such as the calcifying coccolithophores, could be negatively affected (decreasing their calcification rate) by lower pH.[35] Regarding the latter, however, some have suggested that several larger coccolithophore species may be able to increase their calcification in response to anthropogenic CO_2 release.[36] Investigating 40,000 years of deposition in sediment

[29] John M. Pandolfi et al., "Projecting Coral Reef Futures under Global Warming and Ocean Acidification," *Science*, v. 333 (July 22, 2011): 418-422.

[30] Kenneth R. N. Anthony et al., "Coral Reefs Modify Their Seawater Carbon Chemistry—Implications for Impacts of Ocean Acidification," *Global Change Biology*, v. 17, no. 12 (December 2011): 3655–3666.

[31] M. J. Atkinson, B. Carlson, and G. L. Crow, "Coral Growth in High Nutrient, Low-pH Seawater: A Case Study of Corals Cultured at the Waikiki Aquarium, Honolulu, Hawaii," *Coral Reefs*, v. 14, no. 4 (1995): 215-223.

[32] Personal communication, John W. McManus, Director, National Center for Coral Reef Research, Rosenstiel School of Marine and Atmospheric Science, University of Miami, February 21, 2009.

[33] Maoz Fine and Dan Tchernov, "Scleractinian Coral Species Survive and Recover from Decalcification," *Science*, v. 315, no. 5820 (March 30, 2007): 1811.

[34] J. Michael Beman et al., "Global Declines in Oceanic Nitrification Rates as a Consequence of Ocean Acidification," *Proceedings of the National Academy of Sciences of the United States*, v. 108, no. 1 (January 4, 2011): 208-213.

[35] U. Riebesell et al., "Reduced Calcification in Marine Plankton in Response to Increased Atmospheric CO_2," *Nature*, v. 407 (2000): 634-637; and W.M. Balch and V.J. Fabry, "Ocean Acidification: Documenting its Impact on Calcifying Phytoplankton at Basin Scales," *Marine Ecology Progress Series*, v. 373 (2008): 239-247.

[36] P. R. Halloran et al., "Evidence for a Multi-Species Coccolith Volume Change over the Past Two Centuries: Understanding a Potential Ocean Acidification Response," *Biogeosciences*, v. 5 (2008): 1651-1655.

core samples, others find a marked pattern of decreasing calcification of coccolithophores with increasing CO_2 and decreasing bicarbonate.[37]

There is also the concern that decreasing seawater pH may dissolve marine calcium carbonate sediments with potential harm to species and communities residing in and on these sediments.[38] Since many of these organisms provide food or modify habitat for other organisms, the well-being of these carbonate-dependent species will affect other species. Because of these interrelationships, the potential indirect effects of decreased seawater pH on other marine organisms is not well understood.

While some have raised concerns that ocean acidification, by harming calcifying plankton species, could shift ecological balances so as to increase populations of some noncalcifying species, there appears to be no significant relationship between jellyfish abundance and lower pH conditions, and any role of pH in structuring zooplankton communities is believed to be tenuous.[39]

There are also concerns that decreasing seawater pH could alter the ability of some invertebrate organisms to conduct essential biochemical and physiological processes.[40] For example, scientists have found that, when exposed to water of pH 7.7, roughly equivalent to pH levels predicted for the year 2100, sea urchin sperm swam much more slowly. Overall, fertilization fell by 25%, and in almost 26% of cases where the eggs were fertilized, they did not survive long enough to develop into larvae.[41] While marine invertebrates in general, and their early developmental stages in particular, are believed to be more sensitive to environmental disturbance, available data to assess their vulnerability to ocean acidification is contradictory.[42]

In a controlled study at pH values anticipated in 2100, calcification was reduced 28% in the pteropod *Limacina helicina*. These animals continued to grow and produce their shells even under high CO_2, but at a slower rate.[43] Many species, including Pacific salmon, mackerel, herring, cod, and baleen whales, feed upon pteropods. Effects, if any, on the food web are unknown, since pteropod growth is strongly influenced by food availability and temperature, among other things. It is possible that higher temperatures could compensate for growth depression by CO_2.

Coastal areas with upwelling of deeper waters may be at risk from detrimental effects of ocean acidification much more quickly. Concerns have been expressed for benthic calcareous organisms

[37] L. Beaufort et al., "Sensitivity of Coccolithophores to Carbonate Chemistry and Ocean Acidification," *Nature*, v. 476 (August 4, 2011): 80-83.

[38] M. Gehlen, L. Bopp, and O. Aumont, "Short-term Dissolution Response of Pelagic Carbonate Sediments to the Invasion of Anthropogenic CO2: A Model Study," *Geochemistry, Geophysics, and Geosystems*, v. 9 (February 16, 2008): Q02012.

[39] A. J. Richardson and M. J. Gibbons, "Are Jellyfish Increasing in Response to Ocean Acidification?," *Limnology and Oceanography*, v. 53, no. 5 (2008):2040-2045.

[40] Hans-O. Pörtner, "Ecosystem Effects of Ocean Acidification in Times of Ocean Warming: A Physiologist's View," *Marine Ecology Progress Series, v.* 373 (2008): 203-217.

[41] Jon N. Havenhand, Fenina-Raphaeia Buttler, Michael C. Thorndyke, and Jane E. Williamson, "Near-Future Levels of Ocean Acidification Reduce Fertilization Success in a Sea Urchin," *Current Biology*, v. 18, no. 15 (August 2008): 651-652.

[42] S. Dupont and M. C. Thorndyke, "Impact of CO_2-Driven Ocean Acidification on Invertebrates Early Life History—What We Know, What We Need to Know and What We Can Do," *Biogeosciences Discussions*, v. 6 (2009): 3109-3131.

[43] S. Comeau et al., "Key Arctic Pelagic Mollusc (*Limacina helicina*) Threatened by Ocean Acidification," *Biogeosciences Discussions*, v. 6 (2009): 2523-2537.

living in the nearshore shelf along the North American west coast.[44] More specifically, scientists in one of the Intergovernmental Panel on Climate Change (IPCC) scenarios have projected that mussel and oyster calcification, and thus shell strength, could decrease significantly by the end of the 21st century.[45] Recently, oyster growers in the Pacific Northwest have experienced severe larval mortalities resulting in multi-year reproductive failures which may be related to changing ocean chemistry.[46] In addition, laboratory experiments indicate that mussels may exhibit significant signs of deterioration under acidified conditions predicted by the IPCC.[47] Others have attempted to project the timing and severity of the effects of ocean acidification on commercial mollusc harvests.[48]

Vertebrates

Answering the question of how acidification may affect fisheries will likely require the integration of knowledge across multiple disciplines.[49] Although evidence suggests that larval and juvenile fish are more susceptible to changes in ocean water pH than adults, larval and juvenile fish exposed to exceedingly high CO_2 concentrations (more than 100 times current levels) suffered little apparent harm.[50] Fish appear to be among the more tolerant marine animals. These scientists believe that "the relative tolerance of fish may relate to high capacity for internal ion and acid-base regulation via direct proton excretion, and an intracellular respiratory protein that results in a high oxygen-carrying capacity and substantial venous oxygen reserve."[51] Other studies indicate that ocean acidification can impair olfactory discrimination and homing ability of a marine fish such as the clown fish in coral reefs.[52]

Physical Effects of Changing Ocean Chemistry

Concern has also arisen that lower ocean water pH will diminish low-frequency (below 10 KHz) sound absorption in the ocean, increasing noise levels within the auditory range critical for environmental, military, and economic interests.[53] Frequency-dependent decreases to sound absorption related to the current decrease in pH of about 0.1 pH unit may exceed 12%, and an

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[44] Richard A. Feely et al., "Evidence for Upwelling of Corrosive "Acidified" Water onto the Continental Shelf," *Science*, v. 320, no. 5882 (June 13, 2008): 1490-1492.

[45] Frederic Gazeau et al., "Impact of Elevated CO_2 on Shellfish Calcification," *Geophysical Research Letters*, v. 34, no. 7 (April 16, 2007): L07603 (5 p.).

[46] Eric Scigliano, "The Great Oyster Crash," *Onearth* (August 17, 2011); available at http://www.onearth.org/article/oyster-crash-ocean-acidification.

[47] Brian Gaylord et al., "Functional Impacts of Ocean Acidification in an Ecologically Critical Foundation Species," *Journal of Experimental Biology*, v. 214 (August 1, 2011): 2586-2594.

[48] Sarah R. Cooley et al., "Nutrition and Income from Molluscs Today Imply Vulnerability to Ocean Acidification Tomorrow," *Fish and Fisheries* (2011), doi: 10.1111/j.1467-2979.2011.00424.x.

[49] W. J. F. Le Quesne and J. K. Pinnegar, "The Potential Impacts of Ocean Acidification: Scaling from Physiology to Fisheries," *Fish and Fisheries* (2011), doi: 10.1111/j.1467-2979.2011.00423.x.

[50] A. Ishimatsu et al., "Effects of CO_2 on Marine Fish: Larvae and Adults," *Journal of Oceanography*, v. 60, no. 4 (2004): 731-741.

[51] V. J. Fabry et al., "Impacts of Ocean Acidification on Marine Fauna and Ecosystem Processes," *ICES Journal of Marine Science*, v. 65 (2008): 414-432.

[52] Philip L. Munday et al., "Ocean Acidification Impairs Olfactory Discrimination and Homing Ability of a Marine Fish," *Proceedings of the National Academy of Sciences*, v. 106, no. 6 (February 10, 2009): 1848-1852.

[53] Keith C. Hester et al., "Unanticipated Consequences of Ocean Acidification: A Noisier Ocean at Lower pH," *Geophysical Research Letters*, v. 35 (2008): L19601, doe:10.1029/2008FL034913.

anticipated pH decrease of 0.3 pH units by mid-century may result in an almost 40% decrease in sound absorption. It is unknown how marine mammals might be affected by and adapt to an ocean increasingly transparent to sound at low frequencies.

Worst-Case Scenarios

Worst-case scenarios can be particularly hard to characterize, due to unforeseen consequences and possible tipping points, where environmental response may suddenly no longer be directly or linearly related to the causative factors. Although the likelihood of a "worst-case scenario" coming to pass is uncertain and probably low, these circumstances require attention because ignoring them could be potentially disastrous.[54]

Mass extinction events of marine organisms have occurred in geologic history, and some of these events may have had some relationship to significant changes in ocean pH. The fossil record indicates that marine organisms may be quite sensitive to ocean acidification—about 55 million years ago, a large injection of CO_2 into the deep ocean, presumably resulting from a massive methane release, was followed by the extinction of some species of benthic foraminifera.[55] In addition, the extensive loss of marine biodiversity in the Late Triassic, about 200 million years ago, appears to coincide with increased atmospheric CO_2 concentration.[56] Mass extinctions in the geological record correspond to gaps of millions of years in coral reef building, and were likely caused by problems in the carbon cycle, among which acidification is a strong possibility.[57] Some, however, caution that paleo-events may be imperfect analogs to current conditions.[58]

The Intergovernmental Panel on Climate Change has predicted that, under their worst-case scenario of no reduction or control of CO_2 emissions, ocean pH could decrease to 7.7 by 2100. Worst-case scenarios for ocean acidification focus on the potential for disruption of marine ecosystems to the extent that food production from the ocean—finfish, shellfish, and other invertebrates—could be compromised. Physiological changes caused by ocean acidification and affecting ocean primary productivity—phytoplankton—have the potential to alter marine ecosystems significantly, because primary production is at the base of almost all marine food chains.

According to the most recent report on the status of the world's fisheries by the United Nations Food and Agriculture Organization,[59] fisheries supply at least 15% of the animal protein consumed by humans, provide direct and indirect employment for nearly 200 million people worldwide and generate $85 billion annually. Any significant disruption of this industry could have broad dietary as well as economic consequences.

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[54] Stephen Schneider, "The Worst-Case Scenario," *Nature*, v. 458 (April 30, 2009): 1104-1105.

[55] J. C. Zachos et al., "Rapid Acidification of the Ocean During the Paleocene-Eocene Thermal Maximum," *Science*, v. 308 (2005): 1611-1615.

[56] Jennifer C. McElwain, Peter J. Wagner, and Stephen P. Hesselbo, "Fossil Plant Relative Abundances Indicate Sudden Loss of Late Triassic Biodiversity in East Greenland," *Science*, v. 324 (June 19, 2009): 1554-1556.

[57] J. E. N. Veron, "Mass Extinctions and Ocean Acidification: Biological Constraints on Geological Dilemmas," *Coral Reefs*, v. 27 (2008): 459-472, and J. E. N. Veron, *A Reef in Time, the Great Barrier Reef from Beginning to End*, Harvard University Press (2008), 289 p.

[58] Scott C. Doney et al., "Ocean Acidification: The Other CO_2 Problem," *Annual Review of Marine Science*, v. 1 (January 2009): 169-192.

[59] United Nations Food and Agriculture Organization, *The State of World Fisheries and Aquaculture*, Rome, 2008; available at http://www.fao.org/docrep/011/i0250e/i0250e00.htm.

Other consequences of a worst-case scenario include the loss of coral reefs, which, in addition to being unique ecosystems supporting extensive biodiversity, provide coastal protection to mediate storm and wave action as well as the basic structure for many island nations. Reef fish provide subsistence for hundreds of millions of coastal residents, particularly in Southeast Asia. In addition, reef tourism contributes significantly to the economy in the tropics—accounting for about $2 billion dollars of income to Queensland, Australia, about $6 billion dollars of income in the Caribbean (where developing countries can ill afford the loss of it), and a significant portion of the $6 billion that all tourism contributes in the Florida Keys.[60]

What Are the Natural and Human Responses That Might Limit or Reduce Ocean Acidification?

Several natural feedback mechanisms can act to moderate the process of seawater pH change. The less alkaline the ocean becomes, the less CO_2 will be dissolved. In addition, the warmer the seawater becomes, the less CO_2 will dissolve. Speculative questions exist about what might occur should the oceans reach a ceiling (i.e., equilibrium) in their ability to take up CO_2, and atmospheric CO_2 levels continue to increase. Even with increasing concentrations of atmospheric CO_2, scientists predict that the oceans are not likely to reach pH values of less than 7 (neutral).

Our ability to reduce ocean acidification through artificial means is unproven. Proposals have suggested the addition of chemicals to the ocean, such as (1) using iron compounds to stimulate planktonic algae growth, whereby the increased photosynthesis might capture/remove dissolved CO_2;[61] (2) using limestone to neutralize (i.e., buffer) the lower-pH streams and rivers near where they enter oceans and close to sources of limestone, or adding limestone powder directly to the ocean where deeper, lower-pH water upwells;[62] or (3) pumping the calcium bicarbonate byproduct from limestone scrubbers at natural gas power plants into the ocean.[63] Other measures might include habitat restoration/creation, such as planting seagrass. Unless a massive global effort is mounted, these techniques will at best be effective only on a very local scale. In addition, manipulation of ocean chemistry has the potential to damage or otherwise alter the marine environment and ecosystems in unforeseen ways. Reducing CO_2 emissions to the atmosphere and/or removing CO_2 from the atmosphere (i.e., carbon sequestration) currently appear to be the only practical ways to minimize the risk of large-scale and long-term changes to the pH of marine waters. Because of the continuing increase in CO_2 levels in the atmosphere, and its resident time there, decreasing pH of ocean waters will likely continue for decades. Even if atmospheric CO_2 were to return to pre-industrial levels, it could possibly take tens of thousands of years for ocean chemistry to return to a condition similar to that occurring at pre-industrial times more than 200 years ago.[64]

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[60] J. P. G. Spurgeon, "The Economic Valuation of Coral Reefs," *Marine Pollution Bulletin*, v. 24, no. 11 (1992): 529-536, and C. R. Wilkinson, "Global Change and Coral Reefs: Impacts on Reefs, Economies and Human Cultures," *Global Change Biology*, v. 2, no. 6 (1996): 547-558.

[61] Richard Blaustein, "Fertilizing the Seas with Iron," *BioScience*, v. 61, no. 10 (October 2011): 840; See also NOAA, *Report to Congress: Ocean Fertilization: The Potential of Ocean Fertilization for Climate Change Mitigation*, available at http://www.gc.noaa.gov/documents/2010_climate_fert_rept_Congress_final.pdf.

[62] L. D. D. Harvey, "Mitigating the Atmospheric CO_2 Increase and Ocean Acidification by Adding Limestone Powder to Upwelling Regions," *Journal of Geophysical Research*, v. 103 (2008): C04028, 21 p.

[63] Greg H. Rau, "CO_2 Mitigation via Capture and Chemical Conversion in Seawater," *Environmental Science and Technology*, v. 45, no. 3 (2011): 1088–1092.

[64] The Royal Society, *Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide*, Policy Document 12/05

What Is the Federal Government Doing About Ocean Acidification?

Much of the current federal attention to ocean acidification focuses on research to better understand the chemical processes involved and to become better able to predict how ocean ecosystems might respond to decreasing pH.[65]

The National Science Foundation (NSF) was the first federal agency to become involved in research related to ocean acidification. The modern surveys of CO_2 in the oceans can be traced to the NSF-sponsored Joint Global Ocean Flux Study (JGOFS), which originated in recommendations from a National Academies of Science workshop in 1984.[66] The more modern concerns over ocean acidification arose from a May 2004 Paris workshop chaired by the now-president of the National Academy of Sciences, Ralph Cicerone.[67] In April 2005, NSF, the National Oceanic and Atmospheric Administration (NOAA), and the U.S. Geological Survey sponsored a workshop on the impacts of ocean acidification on coral reefs and other marine calcifiers.[68] In Section 701 of P.L. 109-479, Congress called for an 18-month comprehensive national study by the National Research Council of the National Academies of Science on how CO_2 emissions absorbed into the oceans may be altering fisheries, marine mammals, coral reefs, and other natural resources.[69] This study was commissioned by NOAA and NSF in October 2008, and a summary of *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean* was released in late April 2010; the full report was published in September 2010.[70]

The Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM; P.L. 111-11) established the interagency working group on ocean acidification (IWGOA). The IWGOA is chaired by a representative from the National Oceanic and Atmospheric Administration and includes representatives from the National Science Foundation, Bureau of Ocean Energy Management, U.S. Department of State, Environmental Protection Agency, National Aeronautics and Space Administration, U.S. Geological Survey, U.S. Fish and Wildlife Service, and U.S. Navy. The IWGOA was charged with developing a strategic research and monitoring plan to guide federal research on ocean acidification. In 2012, a draft of the *Strategic Plan for Federal Research and Monitoring of Ocean Acidification* was released and sent to the National Research Council for review.[71] The strategic research plan attempts to provide a common vision and

(June 2005), 60 p.

[65] See also Cheryl A. Logan, "A Review of Ocean Acidification and America's Response," *BioScience*, v. 60, no. 10 (November 2010): 819-828.

[66] For additional background, see http://www1.whoi.edu/jgofMission.html.

[67] Ralph Cicerone, "The Ocean in a High CO_2 World," *Eos*, v. 85, no. 37 (September 14, 2004): 351, 353.

[68] J. A. Kleypas et al., *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research*, report of a workshop held April 18-20, 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the U.S. Geological Survey (June 2006), 88 p.

[69] This measure required the Secretary of Commerce to request that the National Research Council study acidification of the oceans and how this process affects the United States. See http://www.noaanews.noaa.gov/stories2008/20081020_oceanacid.html.

[70] Available at http://www.nap.edu/openbook.php?record_id=12904&page=R1. In May 2011, a booklet, *Ocean Acidification: Starting with the Science*, based on the longer report was released, and is available at http://dels.nas.edu/resources/static-assets/materials-based-on-reports/booklets/OA1.pdf.

[71] Interagency Working Group on Ocean Acidification, *Strategic Plan for Federal Research and Monitoring of Ocean Acidification*, March 2012, http://www.st.nmfs.noaa.gov/iwgoa/DRAFT_Ocean_Acidification_Strategic_Research_Plan.pdf.

specific goals to coordinate activities of federal agencies. The plan is organized into the following seven themes,

1. monitoring of ocean chemistry and biological impacts,
2. research to understand responses to ocean acidification,
3. modeling to predict changes in the ocean carbon cycle,
4. technology development and standardization of measurements,
5. assessment of socioeconomic impacts and development,
6. education, outreach, and engagement strategy, and
7. data management and integration.

FOARAM also directed the IWGOA to submit a report to Congress every two years that summarizes federally funded ocean acidification activities. The most recent report for FY2010 and FY2011 identifies funding levels by agency and by the strategic themes used in the strategic research plan. In FY2011, total funding for ocean acidification activities was approximately $29 million. Funding for activities with a primary focus on ocean acidification was approximately $21 million and funding for activities related to ocean acidification was approximately $8 million.[72]

What Is the Congressional Interest in Ocean Acidification?

In comparison to previous sessions of Congress, legislative interest in ocean acidification expanded significantly in the 110th Congress.[73] Congressional attention focused primarily on addressing the cause of ocean acidification—increasing atmospheric CO_2.[74] To date, legislative attention to ocean acidification has focused on authorizing, funding, and coordinating research to increase knowledge about ocean acidification and its potential effects on marine ecosystems.

In the 111th Congress, FOARAM directed the Secretary of Commerce to establish an ocean acidification program within NOAA, established an interagency committee to develop an ocean acidification research and monitoring plan, and authorized appropriations through FY2012 for NOAA and the National Science Foundation. On April 22, 2010, the Senate Commerce, Science, and Transportation Subcommittee on Oceans, Atmosphere, Fisheries, and Coast Guard held a hearing on the environmental and economic impacts of ocean acidification. Several additional measures were introduced in the 111th Congress to address this issue.[75]

The only bill related to ocean acidification that has been introduced during the 113th Congress is the Coral Reef Conservation Act Amendments of 2013 (S. 839). S. 839 would include ocean acidification in the criteria used to evaluate project proposals for studying threats to coral reefs

[72] Interagency Working Group on Ocean Acidification et al., Second Report on Federally Funded Ocean Acidification Research and Monitoring Activities and Progress on a Strategic Research Plan, http://www.st.nmfs.noaa.gov/iwgoa/documents/IWG-OA_Budget_Report-Official_Final_Version.pdf.

[73] For more details on ocean acidification legislation in the 110th Congress, see the section "Climate Change" in CRS Report RL33813, *Fishery, Aquaculture, and Marine Mammal Legislation in the 110th Congress*, by Eugene H. Buck.

[74] See CRS Issue in Focus "Climate Change Science and Technology" available at http://www.crs.gov/pages/subissue.aspx?cliid=3878&parentid=2522&preview=False.

[75] For more details on ocean acidification legislation in the 111th Congress, see the section "Climate Change and Ocean Acidification" in CRS Report R40172, *Fishery, Aquaculture, and Marine Mammal Issues in the 111th Congress*, by Eugene H. Buck and Harold F. Upton.

and developing responses to coral reef losses. On July 30, 2013, the Senate Committee on Commerce, Science and Transportation ordered S. 839 to be reported.

Additional Selected References

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