

Statement of
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Introduction

I thank Chairwoman Bordallo, Ranking Member Brown, and the other Members of the Subcommittee for the opportunity to speak with you today on the future of our wildlife and oceans in a changing climate. My name is Joan Kleypas. I am a Scientist at the National Center for Atmospheric Research in Boulder, Colorado. My personal research has focused on the interactions between marine ecosystems and climate change, with particular emphasis on the impacts of climate change on coral reef ecosystems. I have authored or co-authored between 30 and 40 peer-reviewed scientific journal articles, book chapters, and technical documents, and have presented more than 30 invited talks worldwide. I have co-organized several international workshops on issues related to climate change and marine ecosystems. I currently serve on two committees related to carbon and the oceans: the Ocean Carbon and Biogeochemistry Scientific Steering Committee, and the European CarboOcean International Advisory Board. You have asked me to provide insights on issues related to the known and predicted impacts that climate change is having and is expected to have on wildlife and oceans. My testimony will focus on the emerging problem of ocean acidification. I have worked on this issue since 1998, and have led several efforts to improve our understanding of this process and what it means for ocean life.

Background

A large proportion of the carbon dioxide (CO₂) released to the atmosphere is absorbed by the ocean. A recent inventory of carbon in the oceans estimates that by mid-1990s, the oceans had already taken up nearly half of the total carbon dioxide released by human activities between 1800 and 1994. Without this process, the atmospheric

concentration of carbon dioxide would have risen from 280 ppmv to be about 435 ppmv rather than the current concentration of 380 ppmv. The natural sequestration of carbon dioxide by the oceans thus slows down the build-up of greenhouse gases in the atmosphere.

However, the additional CO₂ in the water column is resulting in “ocean acidification,” the progressive shift of ocean pH toward more acidic conditions. This shift is occurring because carbon dioxide combines with seawater to form carbonic acid, which lowers the pH. Once the concentration of carbon dioxide in the atmosphere reaches twice that of preindustrial times (560 ppmv), the pH of the surface ocean will have decreased from a preindustrial average of about 8.16 to about 7.91. Because pH is reported on a logarithmic scale, this small change in pH represents a rather large increase (78%) in hydrogen ion concentration, with clear implications for biological processes. These changes will also cause shifts in the relative concentrations of other dissolved carbon species in the ocean. Notably, the concentration of the carbonate ion, which is a major building block for the skeletons and shells of many marine organisms, will decrease by about 34%.

Even though the process of ocean acidification was predicted since the 1970s, only recently has this process been verified by large-scale measurements of carbon in the ocean through programs such as the World Ocean Circulation Experiment and the Joint Global Ocean Flux Survey. Based on what we know about ocean pH in the past, the seawater chemistry of the surface ocean is already altered to a state that is considerably outside the range of conditions of the past several hundred thousand years and possibly twenty million years. The surface ocean is everywhere experiencing a decline in pH

(“acidification”). Today, the surface ocean remains saturated with the calcium carbonate minerals aragonite and calcite. The “saturation horizon,” below which these minerals will dissolve, is becoming shallower as the oceans take up more CO₂. Within this century, it is predicted that the saturation horizon for aragonite will reach the surface near the poles, particularly in Antarctica.

In the remaining testimony, the terms “increasing CO₂” and “ocean acidification” are used interchangeably. Although these are not technically the same, the justifying assumption is that increasing atmospheric CO₂ is the absolute driver of ocean acidification.

The Effects of Ocean Acidification on Marine Organisms

The potential effects of ocean acidification on marine biota were not recognized until about a decade ago, when experiments indicated that major groups of marine organisms were affected by ocean acidification. Ocean pH is a fundamental property of seawater that affects almost every aspect of biochemistry. First, it affects organisms physiologically; that is, such basic life functions such as photosynthesis, respiration, growth, etc. Second, in a broad group of organisms that we call “marine calcifiers,” it affects their ability to form their calcium carbonate shells or skeletons. For each, I will outline what we know and also what we don’t know. Most of the information I present here draws from two major reports on ocean acidification published by the Royal Society¹, and by a U.S. effort jointly funded by the National Science Foundation, the

¹ Royal Society, 2005. Ocean acidification due to increasing atmospheric carbon dioxide, Policy Document 12/05. The Royal Society. <http://www.royalsoc.ac.uk/document.asp?id=3249>

National Oceanic and Atmospheric Administration, and U.S. Geological Survey².

Currently, there is much more information regarding the calcification response of marine organisms to ocean acidification than the physiological response.

Physiological response of primary producers and microorganisms: The bulk of the primary production in the oceans is carried out by phytoplankton, unicellular algae that live suspended in the upper few hundred meters of the ocean. These are the foundation for most marine food webs. Marine algae are not as CO₂-limited as terrestrial plants, because they possess a “carbon concentration mechanism.” Thus, CO₂ fertilization does not seem likely for most marine primary producers, and most experiments have confirmed this. One exception is in coccolithophorids, which showed an increase in primary production under conditions of elevated-CO₂ experiments and elevated nutrients; in similar experiments with normal nutrient levels, primary production did not increase. Some true marine plants, such as seagrasses, may be carbon-limited and may grow faster in the future, but this has not been tested. Almost no realistic experiments have been conducted on the vast array of other marine microorganisms.

Physiological response of higher marine organisms. In terms of physiological response, the first question that comes to mind is “will marine organisms be adversely affected by a lowered pH?” Most of the experiments conducted so far were designed to simulate the effects on ocean biota adjacent to deep-injection CO₂ disposal sites, and most were designed to measure acute physiological effects and mortality. Most of the organisms in these tests experienced increasing rates of mortality with decreasing pH, and some of the experiments indicated that physiological stress was apparent even near

² Kleypas JA, RA Feely, VJ Fabry, C Langdon, CL Sabine and LL Robbins. 2006. *Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers. A Guide for Future Research*, Report of a workshop sponsored by NSF, NOAA and the USGS. 88pp. <http://www.isse.ucar.edu/florida/>

slightly elevated concentrations. These experiments did show that some species are not likely to be adversely affected. For example, some copepod and amphipod species appear to be tolerant of even extreme increases in elevated CO₂ concentrations, and/or recover following an acute exposure. These and other species that are adapted to existing extreme environments in the ocean (e.g., the unusual communities associated with hydrothermal vents) are not likely to be directly affected by ocean acidification.

Few experiments have been so far been conducted to test the physiological response of marine organisms to pH changes consistent with projected atmospheric CO₂ concentrations. These experiments have primarily been conducted on mollusks, echinoderms and fish. The basic argument about the effects of ocean acidification on higher-order organisms is that it causes acidosis of animal tissue and body fluids, which can have long-term effects on metabolic functions. A summary of these findings so far are:

- 1) Chronic exposure of fish to lowered pH can cause changes in metabolic states, such as including increased or decreased respiration rates, changes in blood chemistry pH, or changes in enzymatic activities.
- 2) Sea urchins grown in lower-pH waters show an inability to regulate internal acid-base balance, which would limit or inhibit growth. Development of sea urchin larvae is also slowed or abnormal.
- 3) Mollusks grown in lower-pH waters exhibit a slower metabolic rate, a decrease in haemolymph pH, and a decrease in growth rates. Squid appear to be particularly sensitive to ocean acidification because of their high metabolic rate and pH-sensitive blood oxygen transport.

- 4) Some coral species have survived low-pH conditions in the lab for one year, despite the complete dissolution of their skeletons.
- 5) In most species, larval stages are considered more sensitive to pH changes than the adults, because they have less-developed systems for regulating internal pH.

Even though many of these changes are not immediately detrimental to an organism, they may affect long-term growth and reproduction and may thus be harmful at population and species levels.

Effects on marine calcifiers. So far, experiments have been conducted on at least six major groups of calcifying organisms: coccolithophores (microscopic algae); foraminifera (microscopic protozoans); coralline algae (benthic algae); echinoderms (sea urchins and starfish); mollusks (snails, clams, and squid); and corals. While the responses vary somewhat between the major groups, nearly all experiments have that calcification rates decline with decreasing pH. Corals are the best studied among these and the range of experiments indicates that calcification rates will decline by 10-50% if atmospheric CO₂ concentrations reach double the preindustrial concentrations.

The ability of marine calcifiers to adapt to these pH changes has not been adequately tested. Corals that have been grown under decreased pH conditions for a year or more do not show signs of adapting. Calcification rates in one coccolithophore species appears to be maximized at near present-day conditions, which suggests that this species can adapt to new CO₂ conditions. Geological and paleontological data show a waxing and waning of skeletal sizes and thicknesses over time, consistent with changing ocean chemistry, which indicates that many groups do not adapt to such changes.

Ocean acidification not only compromises the ability of these organisms to secrete calcium carbonate, it also increases the rate at which existing calcium carbonate dissolves. This may be particularly important for groups that already exist near the “saturation horizon” of calcium carbonate, such as cold water corals that live in deep waters above the saturation horizon, and planktonic marine snails called “pteropods” that are particularly abundant in Antarctic waters and are an important food species from many commercial species.

There is essentially no information regarding how changes in calcification rate will affect the ability of organisms to survive in nature, and most of what we know is based on assumptions that organisms grow shells and skeletons for a variety of reasons, such as: protection, gathering light for photosynthesis, competing for space, anchoring to the substrate, and reproduction. Suppressing skeletal growth is therefore likely to decrease an organism’s fitness and ability to function within its ecological community. Also, the function of the calcium carbonate may change over the lifetime of an organism. For example, calcium carbonate in a larval echinoderm provides the ballast that allows the larvae to settle onto suitable substrate, but later provides its protective exoskeleton. Recent experiments show that two coral species completely lose their skeletons (through dissolution) when pH is reduced to 7.4 (which would occur if atmospheric CO₂ concentrations exceeds 1200 ppmv); yet they survived in the lab, and once returned to a normal pH, grew new skeletons. This provides a positive note that some coral species could survive ocean acidification, albeit in a much altered state. Indeed, there is evolutionary evidence that some corals may have indeed survived mass extinction events in this way, and provided the stock from which new coral species evolved (over time

spans of millions of years). But the survivability of “naked corals” in the field is questionable, and their ecological role in the coral community would be altered.

The Effects of Ocean Acidification on Marine Ecosystems

Changes in the physiology and calcification rates of marine organisms will undoubtedly affect marine ecosystems and food chains. There are indications that the ranges of some species will be reduced, and that food webs will be altered, including those that support some commercially important fish species. Researchers are beginning to take up the task to find out how such affects will cascade through marine food webs, but at the moment there has been little research on this.

Calcium carbonate is also important at the ecosystem level. Coral reefs exist simply because corals and other organisms secrete calcium carbonate faster than it is removed. Reef structures are important because they 1) support high biodiversity and fisheries, 2) protect many coastlines and provide the quiet conditions necessary for mangroves and seagrass beds, and 3) allow the existence of low-lying coral atolls. The ability of coral reefs to keep up with rising sea level is well documented. This ability is because the amount of calcium carbonate produced by a reef community exceeds the amount that is removed by erosion and dissolution. If calcium carbonate production decreases, then reef-building and the constant supply of coral sediment will also decrease. Mass coral die offs in recent years has led to considerable erosion on some reefs; the Galápagos reefs, for example, were formed over a period of 3000 years, but were eroded away within a decade following the 1982-1983 coral bleaching event. Ocean acidification not only decreases calcification rates on reefs, it also increases dissolution rates, so that net

reef building declines. Any reduction in calcium carbonate increases the potential for island erosion, particularly in the face of rising sea level.

Based on present-day observations and the geological record, it seems certain that ocean acidification will alter our marine ecosystems. The rapid disappearance of marine calcifying organisms in some mass extinction events in Earth history has been attributed, at least in part, to ocean acidification. Unfortunately, the problem of ocean acidification is a relatively new discovery and we are just beginning to understand how far-reaching the effects may be. We have much work to do.

Solutions

Ocean acidification may be one of the greatest environmental risks we face if we continue to allow CO₂ to build up in the atmosphere. The obvious solution is to reduce CO₂ emissions; this will not only decrease ocean acidification, it will decrease many of the other problems associated with climate change. Although seemingly impossible now, should new technologies be developed to not only slow atmospheric CO₂ increases, but actually remove CO₂ from the atmosphere, the current acidification of the upper ocean would be reversed. It is true that much of the carbon absorbed by the oceans has been transported by ocean circulation to deeper depths, and will remain in the ocean for hundreds of years. The upper ocean, however, is in near equilibrium with the atmosphere, and removing CO₂ from either the ocean or the atmosphere causes CO₂ to diffuse across the air-sea interface (gas diffuses from the region of high concentration to low concentration). Thus, restoring the atmosphere to its preindustrial state would restore the surface ocean to its preindustrial pH.

It is tempting to recommend some limit to how acidic the ocean can get before irreparable damage will occur. The “safest” value would be the maximum values experienced during the glacial interglacial cycles (essentially the preindustrial levels). Other values that have been proposed include: the value at which surface waters would become undersaturated with the minerals that organisms need to build shells (550 ppmv)³; or the value at which coral reefs would begin to suffer net erosion (450-1000 ppmv)⁴. However, these are only two of the many other potential thresholds that have not been measured, such as concentrations that: 1) impact fish species or their food resources, 2) impact larval survival and recruitment of important species of fish and shellfish, and 3) cause changes in community composition in ways that affect the ability of the oceans to recycle important nutrients such as carbon, nitrogen, and phosphorus. In reality, there are likely to be a continuum of thresholds, and predicting these is complicated by the problem of “multiple stressors” on marine ecosystems, such as pollution, poor land-use practices, and overfishing.

As technologies to stabilize or reverse CO₂ concentration in the atmosphere are developed, it is not only timely but urgent that we improve our understanding of how ocean acidification will affect marine life across molecular to ecosystem scales. Given the multiple stressors in our environment, actions should be taken to minimize additional stresses to organisms or ecosystems that are particularly vulnerable to ocean acidification (for example, reducing fishing quotas for species that experience lowered reproductive success). Acquiring the information needed to advise policy makers on these issues will

³ Orr, J.C., Fabry, V.J., Aumont, O., et al. (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms, *Nature*, 437, 681–686.

⁴ Yates, K.K. and R.B. Halley (2006) CO₂ concentration and pCO₂ thresholds for calcification and dissolution on the Molokai reef flat, Hawaii, *Biogeosciences*, 3, 357–369.

require coordinated research across multiple institutes and government agencies. In some cases, even basic information on the distribution patterns of major groups of marine organisms is lacking and such information would greatly inform our ability to predict future biological responses. Existing efforts by NOAA and NASA should be expanded to improve monitoring and observations; but much of the key research needed is at the cellular to ecosystem levels and requires basic academic research through both NSF and EPA.

Conclusions

Ocean acidification is occurring now and in all oceans. pH of the surface ocean, where the bulk of ocean production and biodiversity exist, is changing in lock-step with changes in atmospheric CO₂ concentration. The long-term effects of ocean acidification on species and ecosystems are consistent with recent observations that tie mass extinction events of Earth's history to ocean acidification. Evidence from multiple scientific disciplines points to the same conclusion: ocean life is sensitive to changes in ocean pH, and will be increasingly affected by ocean acidification. Many calcifying species are likely to be affected by a decreased capacity to grow and maintain their shells and skeletons. Many other species may be affected physiologically, simply by changes in their internal pH. Because ocean acidification is likely to affect such a broad array of marine organisms, we can expect to see significant changes in marine ecosystems, including those that support commercial fishing. Ocean acidification is an emerging scientific issue, but it is also one of high environmental risk. Because of that, I am deeply

grateful for this opportunity to address this Subcommittee, and I look forward to answering your questions.