MARINE ORGANISMS AND ECOSYSTEMS IN A HIGH-CO2 OCEAN
AND
AN OVERVIEW OF RECOMMENDATIONS FROM THE NATIONAL RESEARCH COUNCIL'S COMMITTEE REPORT ON *DEVELOPMENT OF AN INTEGRATED SCIENCE STRATEGY FOR OCEAN ACIDIFICATION MONITORING, RESEARCH, AND IMPACTS ASSESSMENT*

Statement of

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Good morning Madam Chair, Ranking Member Snowe, and members of the Committee. My name is Jim Barry. I am a senior scientist at the Monterey Bay Aquarium Research Institute (MBARI), located in Moss Landing California, where I have been employed for nearly 19 years. MBARI is a non-profit research and technology institute funded principally by the David and Lucile Packard Foundation where we perform research and technology development to address important issues in ocean science. My research concerns the biology and ecology of marine animals, particularly those inhabiting the deeper waters of the oceans. During the past several years, my studies have focused on the effects of high ocean carbon dioxide levels on marine animals, from either the direct injection of waste CO2 into deep-sea waters or by ocean acidification due to the passive influx of CO2 from the atmosphere. I was a contributing author for the *Special Report on Carbon Capture and Storage* produced by the IPCC (Intergovernmental Panel on Climate Change) in 2005, and am currently serving for the National Research Council as a member of the *Committee on the Development of an Integrated Science Strategy for Ocean Acidification Monitoring, Research, and Impacts Assessment* (hereafter NRC Ocean Acidification Committee). The National Research Council is the operating arm of the National Academy of Sciences, chartered by Congress in 1863 to advise the government on matters of science and technology.

This committee originated as a request from NOAA to the Ocean Studies Board, based on the call from Congress in the Magnuson-Stevens Fishery Conservation and Management Reauthorization Act of 2006, and later the Consolidated Appropriations Act of 2008, to conduct a study of the acidification of the oceans and how this process affects the United States. In addition to NOAA, input and sponsorship of the committee was provided by the National Science and Technology Council Joint Subcommittee on Ocean Science and Technology (JSOST), the National Science Foundation (NSF), and the U.S. Geological Survey (USGS).

I commend the Committee for convening a hearing on, *The Environmental and Economic Impacts of Ocean Acidification,* – the other CO2 problem, due to the growing concern that this phenomenon may have important effects on marine organisms and ecosystems, as well as ecosystem services of great value to society. The history of ocean acidification research is relatively short. The notion that increasing carbon dioxide emissions absorbed through the sea surface are causing a change in ocean chemistry and may have important consequences for ocean biology was argued in the 1970s (Caldeira and Wickett, 2005). During the past ten to fifteen years, however, several studies and workshop reports have concluded that the very rapid and massive influx of CO2 emissions into the oceans (now over 1 million tonnes of CO2 per hour) could have very significant effects on marine ecosystems (Kleypas et al. 1999; Raven et al. 2005; Fabry et al. 2008; Kleypas et al. 2006; Doney et al. 2009).

In my testimony, I would like to address two main themes. First, I will provide my personal perspective based on my own studies and others concerning the potential effects of ocean acidification on the biology of marine organisms and how these affects are expected to scale up to ecosystem services important to society. Second, I will provide an overview of the key points and recommendations from the NRC Ocean Acidification Committee's report on *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*
The key points of my personal testimony are as follows:

- Ocean acidification is changing the chemistry of the oceans at a scale and magnitude greater than thought to occur on Earth for many millions of years, and is expected to cause changes in the growth and survival of a wide variety of marine organisms, potentially leading to massive shifts in ocean ecosystems.

- Ocean acidification, like other sources of environmental variation, directly affects the physiological performance of organisms, which can respond individually by acclimation (tolerance), or collectively as a species by adaptation or extinction. Sensitivity to ocean acidification is known to vary among organisms and habitats, including “winners” and “losers”, with some photosynthetic organisms apparently benefiting, while the performance of animals is generally impaired.

- Future changes in marine ecosystems expected to occur due to ocean acidification are poorly understood for most habitats, and difficult to predict from short-term studies of individual species, a research approach that has dominated this field to date. It is expected that biodiversity in many ecosystems may decrease due to the generally negative impacts of ocean acidification on marine animals, thereby impairing ecosystem function. Severe changes could lead to ecological “tipping points”.

- Ocean goods and services important to society (e.g. marine fisheries), are dependent on the healthy function of marine ecosystems. Although it remains unclear how marine fisheries will be affected, changes in the photosynthesis at the base of the food chain and shifts in the growth, survival, and productivity of higher trophic levels due to ocean acidification are expected to lead to important changes in ecosystems.

1. Ocean chemistry is changing rapidly due to the influx of fossil fuel carbon dioxide.

Roughly 40 percent of all fossil fuel emissions now reside in the oceans (Sabine and Tanhua 2010), and the ocean surface is 25-30 percent more acidic than prior to human fossil fuel use. Increasing carbon dioxide emissions are expected to increase ocean acidity (pH) by ~200 percent by the end of this century, with even greater changes beyond 2100. In addition to increased acidity, ocean acidification causes higher carbon dioxide concentrations in seawater and a reduction in the saturation state of calcium carbonate minerals important for shells and skeletal formation in many marine organisms. This change in ocean chemistry is far more rapid and larger than has occurred throughout the past 800,000 years and perhaps as long as 25 million years, 10 million years before the first hominids appeared on Earth. Eventually, over 85 percent of all emissions will reside in the ocean, and this carbon dioxide will mix throughout the depths of the oceans.

2. Ocean acidification acts on the physiology of individuals

The response of organisms to ocean acidification depends upon physiological adaptations that have allowed them to survive and function in ocean ecosystems through their evolutionary history. In order to be successful – to survive, grow, and reproduce -, organisms must maintain physiological function throughout a range of environmental variation or suffer reduced or impaired performance. As ocean chemistry diverges distinctly from the natural range of variation experienced through their recent evolutionary history, the tolerance of species is expected to decline.

Several key physiological functions are affected by ocean acidification in marine organisms including photosynthesis, calcification, respiration, internal acid-base balance, and metabolic rates. Photosynthesis has been observed to increase in some species in high-CO2 waters, although rates of calcification may be reduced. Ocean acidification has been shown in general to reduce the rates of calcification in many marine organisms, due to the reduction in the saturation of calcium carbonate minerals in seawater (e.g. Doney et al. 2009; Fabry et al. 2008). Ocean acidification can also disturb the internal acid-base balance of organisms, leading to reduced function of enzymes involved in a wide variety of fundamental biological processes. Increased seawater acidity can also impair oxygen transport and lead to lower metabolic rates in many organisms, which in turn limits their aerobic activity (e.g. chasing prey or escaping predators).

Maintaining efficient physiological function in more acidic waters has been shown in some taxa to increase the energy required to cope with these stresses. This increased "cost of living" is expected to reduce the energy available for growth and reproduction in individuals. Reduced performance by individuals is expected to impact the entire species, leading to reduced abundance and productivity, and a greater likelihood of extinction.

Though limited, research to date indicates that there will be "winners" and "losers" in a high CO2 ocean. In general, photosynthetic species may benefit in some ways from higher CO2 levels in seawater, particularly some seagrasses (reviewed in Doney et al. 2009). Shifts in photosynthesis rates could lead to massive changes in the dominant phytoplankton species forming the base of marine food webs, with effects reverberating throughout pelagic ecosystems. Most animals, however, either do not benefit or have exhibited various combinations of impaired shell or skeletal formation (calcification), and reduced rates of growth, reproduction, or survival. Corals, particularly those forming aragonite (a form of calcium carbonate) skeletons appear particularly vulnerable to ocean acidification, and along with other aragonitic taxa, may be the ecological 'losers' in the future high CO2 ocean.

There is considerable variation among organisms in coping with physiological stress caused ocean acidification. Adaptations that allow some organisms to have very active lifestyles, with a high capacity for gas exchange (respiration) and metabolism (e.g. actively swimming fishes or many mollusks), also preadapt these species for some of the stresses of ocean acidification. However, even though they may be able to tolerate ocean acidification, they may nevertheless experience reduced performance. In contrast, more sedentary animals may have less extra energy for coping with ocean acidification. Sensitivity also has been shown to vary among life stages of species and among habitats. Some deep-sea taxa have been shown to be sensitive to even moderately acidic waters (Barry et al. 2004, 2005), and the physiological tolerance of various higher taxa (fishes, crustaceans) to ocean acidification decreases greatly with depth (Seibel and Walsh 2003; Pane and Barry 2007).

3. Future changes in marine ecosystems due to ocean acidification are understood poorly

"Scaling up" from the effects of ocean acidification on individuals to entire ecosystems is difficult. Except for a series of experiments on marine plankton communities, most research on ocean acidification has been performed on individual species, thereby limiting our understanding of population and ecosystem-level effects of a high-CO2 ocean.

The function of marine ecosystems depends upon their biodiversity - the wide variety of species in the habitat. Biodiversity forms a biological network that functions though the interactions between species and with their environment. Predation, competition, and other interactions among species, as well as the effects of environmental variation on species, determine how and how much energy flows from primary producers at the base of food chains to top predators.

Biological networks with greater diversity (i.e. more species) are thought to be more stable, more resistant to disturbances, and allow more efficient energy flow to top predators. In part, this is related to overlapping ecological roles among species – the ability of multiple species to perform the same or similar functions in food webs. For example, if one species of prey goes extinct, a predator will be able to find another to take its place. Although we still don't know how ocean acidification will affect ecosystems, it is expected that ecosystem function will degrade if biodiversity is lost, and may reach an ecological tipping point if key species are reduced or removed. Studies of large marine ecosystems housing marine fisheries indicate that lower biodiversity is associated with low catch rates, greater variability, and higher chances of fisheries collapse (Worm et al. 2006). And though the specific effects of ocean acidification on marine fisheries in the future remains uncertain, loss of biodiversity caused by ocean acidification and other environmental perturbations can affect ecosystem function, potentially leading to ecological 'tipping points'.

4. Ocean resources and services important to society depend upon the healthy ecosystems

Humanity depends on the function of ocean ecosystems for a range of resources and services, from processes as fundamental as oxygen production by marine phytoplankton, to shoreline protection, fisheries and aquaculture harvests, and recreational or spiritual experiences. It is my personal opinion that although predicting changes in ecosystem function due to ocean acidification is difficult, key elements of some ecosystems appear to be at high risk due to the expected reduction in calcification (and perhaps other related physiological processes) with increasing ocean acidity. Tropical coral reefs, deep-sea coral reefs, and mollusk-dominated food webs in high latitude regions may experience reductions in calcification that lead to important ecosystem changes. Consequently, societies depending on tropical reef systems may experience significant ecological and economic disruption. On the other hand, the potential increase in photosynthetic rates by phytoplankton could increase the energy available within some ecosystems, potentially leading to increased production at higher trophic levels as long as food webs function efficiently. Finally, although there will be losers and winners throughout ecosystems, I expect society, along with most ecosystems, will be on the losing side of this 'game'. Throughout Earth history, periods of rapid environmental change have often (but not always) led to a contraction in biodiversity that disrupted the function of ecosystems.

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Key Findings from the NRC Committee Report on *Ocean Acidification: A National Strategy to Meet the Challenges of a Changing Ocean*

The ocean has absorbed a significant portion of all human-made carbon dioxide emissions, benefiting society by moderating the rate of climate change, but also causing unprecedented changes to ocean chemistry. Carbon dioxide taken up by the ocean decreases the pH of the water and leads to a suite of chemical changes collectively known as ocean acidification. The long term consequences of ocean acidification are not known, but are expected to result in changes in many ecosystems and the services they provide to society. This report, requested by Congress, reviews the current state of knowledge and identifies gaps in understanding, with the following key findings.

1. **Ocean chemistry is changing at an unprecedented rate and magnitude due to human-made carbon dioxide emissions.** The average pH of ocean surface waters has decreased by about 0.1 pH unit —from about 8.2 to 8.1–since the beginning of the industrial revolution, and model projections show an additional 0.2-0.3 drop by the end of the century, even under optimistic scenarios of carbon dioxide emissions.

2. **Changes in seawater chemistry are expected to affect marine organisms that use carbonate to build shells or skeletons.** For example, decreased concentrations of calcium carbonate make it difficult for organisms such as coral reef-building organisms and commercially important mollusks like oysters and mussels to grow or to repair damage. If the ocean continues to acidify, the water could become corrosive to calcium carbonate structures, dissolving coral reefs and even the shells of marine organisms.

3. **It is currently not known how various marine organisms will acclimate or adapt to the chemical changes resulting from acidification**. Based on current knowledge, it appears likely that there will be ecological winners and losers, leading to shifts in the composition of many marine ecosystems.

4. **The committee finds that the federal government has taken positive initial steps by developing a national ocean acidification program.** The recommendations in this report provide scientific advice to help guide the program.

5. **More information is needed to fully understand and address the threat that ocean acidification may pose to marine ecosystems and the services they provide.** Research is needed to assist federal and state agencies in evaluating the potential impacts of ocean acidification, particularly to:
   - understand processes affecting acidification in coastal waters;
   - understand the physiological mechanisms of biological responses;
   - assess the potential for acclimation and adaptation;

- investigate the response of individuals, populations, and communities;
- understand ecosystem-level consequences;
- investigate the interactive effects of multiple stressors;
- understand the implications for biogeochemical cycles; and
- understand the socioeconomic impacts and informing decisions.

6. **The national ocean acidification will need to adapt in response to new research findings.** Because ocean acidification is a relatively new area of research, the Program will need to adapt in response to findings, such as the identification of important biological metrics, analyses of the socioeconomic impact of ocean acidification, and inclusion of concerns from stakeholder communities.

7. **A global network of chemical and biological observations is needed to monitor changes in ocean conditions attributable to acidification.** Existing observation systems were not designed to monitor ocean acidification, and thus do not provide adequate coverage or measurements of carbon parameters, such as total alkalinity, pH, and dissolved inorganic carbon, or biological constituents such as nutrients, oxygen, and chlorophyll. Adding sites in vulnerable ecosystems, such as coral reefs or polar regions, and areas of high variability, such as coastal regions, would improve the observation system.

8. **International collaboration will critical to the success of the program**. Ocean acidification is a global problem that requires a multinational research approach. Such collaborations also afford opportunities to share resources, including expensive large-scale facilities for ecosystem-level manipulation, and expertise that may be beyond the capacity of a single nation.

9. **The national ocean acidification program should support the development of standards for measurements and data collection and archiving to ensure that data is accessible and useful to researchers now and in the future.** Steps should be taken to make information available to policy makers and the general public in a timely manner.