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HEARING ON
A RATIONAL DISCUSSION OF CLIMATE CHANGE:
THE SCIENCE, THE EVIDENCE, THE RESPONSE

BEFORE THE
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Introduction

Chairman Baird and members of the Subcommittee, thank you for giving me the opportunity to speak with you today on the evidence of climate change and ocean acidification. My name is Richard Feely. I am a Senior Scientist at the Pacific Marine Environmental Laboratory of the National Oceanic and Atmospheric Administration (NOAA) in Seattle, WA. My personal area of research is the study of the oceanic carbon cycle and ocean acidification processes. I have worked for NOAA for 36 years and have published more than 300 peer-reviewed scientific journal articles, book chapters and technical reports. I serve on the U.S. Ocean Carbon and Biogeochemistry Scientific Steering Committee and I am the co-chair of the U.S. Repeat Hydrography Program Scientific Oversight Committee. I am also a member of the International Scientific Advisory Panel for the European Program on Ocean Acidification and the Interagency Working Group on Ocean Acidification, under the Joint Subcommittee on Science and Technology. Today I will discuss observed ocean acidification, its impacts on marine life, and potential economic impacts.

What is Ocean Acidification?

Over the past two and a half centuries, the release of carbon dioxide (CO_2) from our collective industrial and agricultural activities has resulted in atmospheric CO_2 concentrations that have increased from about 280 parts per million (ppm) to 392 ppm. The atmospheric concentration of CO_2 is now higher than experienced on Earth for at least the last 800,000 years, and is expected to continue to rise, leading to significant temperature increases in the atmosphere and oceans by the end of this century. To this day, the oceans have absorbed more than 500 billion tons of carbon dioxide from the atmosphere, equivalent to about one third of the anthropogenic CO_2 emissions released during this period (Sabine and Feely, 2007). This natural process of absorption has benefited humankind by significantly reducing the greenhouse gas levels in the atmosphere and reducing the magnitude of global warming experienced thus far.

Unfortunately the ocean's daily uptake of 22 million tons of CO_2 is having a significant impact on the chemistry and biology of the oceans. Over the last three decades, NOAA, the National Science Foundation and the Department of Energy have co-sponsored repeat hydrographic and chemical surveys of the world's oceans, documenting their response to increasing amounts of carbon dioxide being emitted to the atmosphere by human activities. These surveys have confirmed the oceans are absorbing increasing amounts of carbon dioxide. Both the hydrographic surveys and modeling studies reveal that chemical changes in seawater resulting from absorption of carbon dioxide are increasing the acidity of seawater or lowering of its pH. A drop in pH indicates an increase in acidity, as on the pH scale 7.0 is neutral, with points lower on the scale being "acidic" and points higher on the scale being "basic" (Raven *et al*, 2005; Feely *et al*., 2009). Scientists have estimated that the pH of our ocean surface waters has already fallen by about 0.1 units from an average of about 8.2 to 8.1 since the beginning of the industrial revolution. Because the pH scale, like the Richter scale, is logarithmic, a 0.1 unit decrease represents approximately a 26 percent increase in acidity.

Future predictions indicate that the oceans will continue to absorb carbon dioxide and become even more acidic. (Feely *et al.*, 2004; Orr *et al.*, 2005; Caldeira and Wickett, 2005; Doney *et al*., 2009a; Feely *et al.*, 2009). The United Nation's Intergovernmental Panel on Climate Change emission scenarios and numerical circulation models indicate that by the middle of this century, future atmospheric carbon dioxide levels could reach more than 500 ppm, and near the end of the century they could be as much as 700-800 ppm (Orr *et al*., 2005). This would result in a surface water pH decrease of approximately 0.3 pH units as the ocean becomes more acidic, which is equivalent to a doubling of acidity. To put this in historical perspective, the resulting surface ocean pH would be lower than it has been for at least the last 20 million years (Feely et al., 2004). When CO_2 reacts with seawater, fundamental chemical changes occur that cause seawater to become more acidic. The interaction between CO_2 and seawater also reduces the availability of carbonate ions, which play an important role in shell formation for a number of marine organisms such as corals, marine plankton, and shellfish. This phenomenon, which is commonly called "ocean acidification," could affect some of the most fundamental biological and geochemical processes of the sea in coming decades. This rapidly emerging issue has created serious concerns across the scientific and marine resource management communities.

Evidence of Ocean Acidification Effects on Coral Reefs

Many marine organisms that produce calcium carbonate shells are negatively impacted by increasing carbon dioxide levels in seawater (and the resultant decline in pH). For example, increasing ocean acidification has been shown to significantly reduce the ability of reef-building corals to produce their skeletons, affecting growth of individual corals and making the reef more vulnerable to erosion (Kleypas *et al*., 2006; Doney *et al*., 2009a; Cohen and Holcomb, 2009). Some estimates indicate that, by the end of this century, coral reefs may erode faster than they can be rebuilt. This could compromise the long-term viability of these ecosystems and perhaps impact the thousands of species that depend on the reef habitat. Decreased calcification may also compromise the fitness or success of these organisms and could shift the competitive advantage towards organisms that are not dependent on calcium carbonate. Carbonate structures are likely to be weaker and more susceptible to dissolution and erosion in a more acidic environment. Furthermore, recent findings suggest that the calcium carbonate cementation that serves to bind the reef framework together may be eroded (Manzello *et al*., 2008). Such effects could compromise reef resiliency in the face of other threats, such as thermal stress, diseases, storms, and rising sea level (e.g., Silverman *et al.*, 2009). For example, in CO_2-enriched waters around the Galapagos Islands, reef structures were completely eroded to rubble and sand in less than 10 years following an acute warming disturbance (1982–83 El Niño event; Manzello *et al*., 2008). In long-term laboratory and mesocosm experiments, or contained laboratory model ecosystems under controlled conditions, corals that have been grown under lower pH conditions for periods longer than one year have not shown any ability to adapt their calcification rates to the lower pH levels. In fact, two studies showed that the projected increase in CO_2 is sufficient to dissolve the calcium carbonate skeletons of some coral species (Fine and Tchernov, 2007; Hall-Spencer *et al*., 2008).

Evidence of Ocean Acidification Effects on Fish and Shellfish

Ongoing research is showing that decreasing pH may also have deleterious effects on commercially important fish and shellfish larvae. Both king crab and silver seabream larvae exhibit very high mortality rates in CO_2-enriched waters (Ishimatsu *et al*., 2004). Some of the experiments indicated that other physiological stresses were also apparent. Exposure of some fish and shellfish to lower pH levels can cause decreased respiration rates, changes in blood chemistry, and changes in enzymatic activity. The calcification rates of the edible mussel (*Mytilus edulis*) and Pacific oyster (*Crassostrea gigas*) decline linearly with increasing CO_2 levels (Gazeau *et al*. 2007). Squid are especially sensitive to ocean acidification because it directly impacts their blood oxygen transport and respiration (Pörtner *et al*., 2005). Sea urchins raised in lower-pH waters show evidence for inhibited growth due to their inability to maintain internal acid-base balance (Kurihara and Shirayama, 2004). The supply of these commercially valuable species is in jeopardy from ocean acidification.

Scientists have also seen a reduced ability of marine algae and free-floating plants and animals to produce protective carbonate shells (Feely *et al*., 2004; Orr *et al*., 2005; Doney *et al*., 2009b). These organisms are important food sources for other marine species. One type of free-swimming mollusk called a pteropod is eaten by organisms ranging in size from tiny krill to whales. In particular, pteropods are a major food source for North Pacific juvenile salmon, and also serve as food for other salmon species, mackerel, pollock, herring, and cod. Other marine calcifiers, such as coccolithophores (microscopic algae), foraminifera (microscopic protozoans), coralline algae (benthic algae), echinoderms (sea urchins and starfish), and mollusks (snails, clams, and squid) also exhibit a general decline in their ability to produce their shells with decreasing pH (Kleypas *et al*., 2006; Fabry *et al*., 2008).

Evidence of Ocean Acidification Effects on Marine Ecosystems

Since ocean acidification research is still in its infancy, it is impossible to predict exactly how the individual species responses will cascade throughout the marine food chain and impact the overall structure of marine ecosystems. It is clear, however, from both the existing data and from the geologic record that some coral and shellfish species will be negatively impacted in a high-CO_2 ocean. The rapid disappearance of many calcifying species in past extinction events has been attributed, in large part, to ocean acidification events (Zachos *et al*., 2005; Vernon, 2008). Over the next century, if CO_2 emissions continue to increase as predicted by the IPCC CO_2 emissions scenarios, humankind may be responsible for increasing oceanic CO_2 and making the oceans more corrosive to calcifying organisms than at anytime in the last 20 million years. Thus, the decisions that are made about carbon dioxide emissions over the next few decades will probably have a profound influence on the makeup of future marine ecosystems for centuries to millennia.

Potential Economic Impacts of Ocean Acidification

The impact of ocean acidification on fisheries and coral reef ecosystems could reverberate through the U.S. and global economy. The U.S. is the third largest seafood consumer in the world with total consumer spending for fish and shellfish around $70 billion per year. Coastal and marine commercial fishing generates upwards of $35 billion per year and employs nearly 70,000 people (NOAA Fisheries Office of Science and Technology; http://www.st.nmfs.gov/st1/fus/fus05/index.html). In a recent study by Cooley and Doney (2009) the total value of U.S. commercial harvests from U.S. waters and at-sea processing was approximately $4 billion in 2007. Almost a quarter (24%) of all U.S. commercial harvest revenue was from harvesting fish that prey directly on calcifying organisms. Different species dominate different regional revenues; mollusks are more important in the New England and mid- to south-Atlantic regions, crustaceans contribute greatly to New England and Gulf of Mexico fisheries, and predators dominate the Alaskan, Hawaiian, and Pacific territory fisheries. On the west coast shellfish industries bring in more than $110 million in revenue each year. Bivalves, such as oysters, also filter marine and estuarine waters and create habitat for other species, serving important ecosystem services (NOAA OA Plan, 2009; Feely *et al*., 2010). Since 2006, some oyster hatcheries in the Pacific Northwest region have experienced mass mortalities of oyster larvae in association with a combination of factors, including unusually saline surface waters and the upwelling of cold, CO2- and nutrient-rich waters (Feely *et al*., 2008).

Healthy coral reefs are the foundation of many viable fisheries, as well as the source of jobs and businesses related to tourism and recreation. Increased ocean acidification may directly or indirectly influence the fish stocks because of large-scale changes in the local ecosystem dynamics. It may also cause the dissolution of the newly discovered deepwater corals in the West Coast and Alaskan Aleutian Island regions, where many commercially important fish species in this region depend on this particular habitat for their survival. In the Florida Keys alone, coral reefs attract more than $1.2 billion in tourism annually (English *et al*., 1996). In Hawaii, reef-related tourism and fishing generate $360 million per year, and their overall worth has been estimated at close to $10 billion (Cesar *et al*., 2002). In addition to sustaining commercial fisheries, tourism, and recreation, coral reefs also provide vital protection to coastal areas that are vulnerable to storm surges and tsunamis.

NOAA Ocean Acidification Research

Ocean acidification is an important new scientific frontier which we must understand better given its potentially adverse consequences. NOAA research activities offer significant contributions to improving our understanding and assessing the impacts of this rapidly emerging issue. In response to the Federal Ocean Acidification Research and Monitoring Act of 2009 (FOARAM Act), NOAA is in the process of hiring a permanent ocean acidification program director as a final step to the establishment of a new NOAA ocean acidification program, per section 12406 of the FOARAM Act. NOAA has also developed an integrated Ocean Acidification and Great Lakes research and long-term monitoring plan for assessing climate change impacts on living marine resources and the businesses and communities that depend on their sustainable use. The primary goals of this plan are to:

- Assess the ecological and socioeconomic effects of ocean acidification on commercial fish species and the greater ecosystems on which they rely;

- Develop and provide sensors to monitor ocean acidification both for fixed platforms and for mobile use by researchers and coastal managers in the field;

- Determine and monitor the status and potential effects of ocean acidification on coral reefs and other protected areas such as National Marine Sanctuaries; and

- Expand carbonate analytical capabilities at NOAA science centers in order to meet the growing demand for quality control on samples being collected both in the field from U.S. waters and from researchers studying the impacts of ocean acidification on critical species through laboratory experiments.

The results of this research will help to inform future strategies to help communities, ecosystems, and industries respond to ocean acidification. The increased research capabilities will complement, accelerate, and enhance current NOAA ocean acidification activities within the Office of Oceanic and Atmospheric Research, National Ocean Service, and National Marine Fisheries Service.

Interagency Planning

The FOARAM Act directed the Joint Subcommittee on Ocean Science and Technology (JSOST) of the National Science and Technology Council to create an Interagency Working Group on Ocean Acidification (IWG-OA), chaired by NOAA. The IWG-OA was charged with developing a strategic plan for Federal research and monitoring on ocean acidification that will provide for an assessment of the impacts of ocean acidification on marine organisms and marine ecosystems and the development of adaptation and mitigation strategies to conserve marine organisms and marine ecosystems. The IWG-OA has developed a draft strategic plan that is presently undergoing review, in preparation for delivery in early spring 2011 as requested by the FOARAM Act.

Conclusion

In conclusion, ocean acidification is caused by the buildup of carbon dioxide and other acidic compounds in the atmosphere and is expected to have significant impacts on marine ecosystems. Results from laboratory, field and modeling studies, as well as evidence from the geological record, clearly indicate that marine ecosystems are highly susceptible to the increases in oceanic CO_2 and the corresponding decreases in pH. Because of the very clear potential for ocean-wide impacts of ocean acidification at all levels of the marine ecosystem, from the tiniest phytoplankton to zooplankton to fish and shellfish, we can expect to see significant impacts that are of immense importance to humankind. Ocean acidification is an emerging scientific issue and much research is needed before the breadth and magnitude of ecosystems' responses are well understood. However, to the limit that the scientific community understands this issue right now, the potential for environmental, economic and societal risk is quite high, hence demanding serious and immediate attention. Thank you for giving me the opportunity to address this Subcommittee. I look forward to answering your questions.

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