US Senate Committee on Commerce, Science, and Transportation

Oceans, Atmosphere, Fisheries, and Coast Guard

Field Hearing: Effects of Climate Change on Marine and Coastal Ecosystems in Washington

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1. Statement of Problem

Industrial and agricultural releases of carbon dioxide (CO_2) to the atmosphere have accelerated over the past 250 years, with the result that levels of CO_2 in the atmosphere now are higher than at any time in the past 650,000 years (Feely et al. 2008, and references therein). The oceans absorb about 30 million metric tons of this atmospheric CO_2 daily. Dissolution of atmospheric CO_2 in seawater causes the pH of seawater to decline (become more acidic) and reduces carbonate saturation levels. Temperate upwelling systems, high-latitude systems, and urbanized coastal areas all are likely to be substantially impacted by changes in pH and carbonate saturation within the next few decades. Concerted, sustained efforts must be made now to improve the state of the science and to incorporate science into decisions that will minimize risk to social, economic, and ecological systems.

2. State of the Science

The biological and ecological impacts of declining pH and carbonate saturation (jointly referred to as 'ocean acidification') in temperate and high-latitude ecosystems are poorly known but are predicted to affect biological processes and ecological interactions across multiple scales of time and space (e.g., Hutchins et al., 2007; Riebesell et al., 2007; Engel et al., 2005; Delille et al., 2005). Ecologically important species (e.g., keystone species, foundation species, ecosystem engineers) are likely to be negatively impacted, causing unforeseen and undesirable changes in marine ecosystems and in the provision of goods and services to humans. Commercially important species are among the species likely to be negatively impacted, influencing rates of harvest among wild and cultured species, ultimately reducing the availability of human food provided from the ocean.

Biological responses to ocean acidification will vary by species. Although calcifying organisms (algae and animals with calcareous shells or skeletons) are considered to be particularly vulnerable to ocean acidification, non-calcifying organisms also will be affected. Negative impacts are likely to include reductions in growth, reproduction, survivorship, aerobic capacity, thermal tolerance, and disease resistance. Direct lethal impacts will cause mortality in some marine organisms. Other organisms will experience sub-lethal impacts that could have substantial negative ecosystem effects. For example, sub-lethal responses that have been observed in recent experiments include but are not limited to:

- Changes in size: sea urchins reared under high-CO_2 conditions were smaller than urchins reared in normal sea water (G. Hofmann, UC Santa Barbara, unpublished data)
- Changes in morphology: calcified larvae of sand dollars showed subtle changes in morphology when reared under high-CO_2 conditions. The observed morphological changes impaired larval swimming behavior, suggesting that survivorship and recruitment of larvae could be reduced (T. Clay and J. Kershner, University of Washington, unpublished data)
- Reduced thermal tolerance: calcified larvae of sea urchins were able to build skeletons but were less tolerant of thermal stress when reared under high-CO_2 conditions (G. Hofmann, UC Santa Barbara, unpublished data)
- Reduced growth rates: microscopic stages of two kelp species exhibited slower growth when grown under high-CO_2 conditions. Although preliminary, this result suggests that kelps and other non-calcified algae could be negatively impacted by ocean acidification (T. Klinger, unpublished data)

3. Ecosystem Impacts

Ecosystem impacts of ocean acidification are difficult to predict given the current state of the science. Likely impacts include:

- Changes in food web structure and function (e.g., changes in the distribution and abundance of prey species and their predators; increased vulnerability of prey species due to slower growth and reduced calcification)
- Changes in species assemblages. Species that respond negatively to ocean acidification are likely to be replaced by others that are less sensitive to changing ocean chemistry. New assemblages are unlikely to provide the same goods and services that we rely on now.
- Changes in the distribution and abundance of biologically-formed (biogenic) habitat. Early evidence suggests that reef-forming organisms, especially those with calcified skeletons, and canopy-forming kelps could be negatively impacted by ocean acidification, with consequences for other organisms such as fish that utilize or depend on such habitats.

4. Fisheries Impacts

Impacts of ocean acidification on commercial and recreational fisheries are poorly known. Impacts are likely to be mediated through effects on growth and survivorship of larvae and juveniles and through prey availability for all life history stages. Likely impacts include:

- Changes in the distribution and abundance of target species
- Changes in the size and condition of harvested fish and shellfish

5. Synergistic Effects

The biological and ecological effects of ocean acidification are likely to be exacerbated by increasing ocean temperature, declining concentrations of dissolved oxygen, and other physical stressors such as ultraviolet radiation. Synergistic effects can lead to unpredictable ecological responses such as non-linear dynamics, thresholds, and tipping-points.

6. Biological Adaptation and Evolutionary Potential

The potential for biological adaptation to ocean acidification is poorly known. Populations with diversity in genes that regulate response to pH and carbonate saturation are more likely to persist over time than are those with little genetic diversity. Because we do not yet know which species or populations exhibit such genetic diversity, it is essential to maintain evolutionary potential by conserving both species diversity and genetic diversity. The potential for biological adaptation will be constrained by loss of biological diversity and by the rapid rate at which environmental change is occurring.

7. Gaps in Knowledge

Although there now exists compelling evidence that the pH of the ocean is changing due to absorption of anthropogenic CO_2, our understanding of local and regional conditions and impacts is limited. Among the existing gaps are the following:

- Status and trends in seawater chemistry (pH, carbonate saturation, temperature, dissolved oxygen, and other water properties) at spatial and temporal scales relevant to regional research, management, and decision-making
- Status and trends in local populations vulnerable to ocean acidification and the combined effects of multiple stressors
- Range of responses among key ecosystem elements and commercially important species
- Potential for biological adaptation; evolutionary potential
- Non-linear dynamics, thresholds, and tipping-points in ecological responses to ocean acidification and multiple stressors

8. Research Needs

The state of the science necessitates that new research be conducted. Only through direct experimentation will we be able to adequately parameterize models to forecast ecosystem change in the ocean and guide strategies to mitigate impacts on social, economic, and ecological systems. Effective research will require that investigations be conducted across multiple scales of organization, from genes to ecosystems, and at appropriate time scales. Satisfying these research needs will require that substantial new funds are made available to the research community. Research priorities include but are not limited to:

- More intensive and extensive monitoring of seawater chemistry and associated physical properties to detect physical change as it occurs
- Improved baseline biological data to detect ecological change as it occurs, and to link ecological change to chemical change
- Establishment of chemical and biological time-series at sentinel sites
- Experimentation to characterize physiological responses and differential gene expression under changing conditions and to determine the potential for biological adaptation
- Experimentation to determine the range of biological responses among key ecosystem elements and species of commercial importance
- Experimentation to determine interactions between species, including food web interactions, under conditions of ocean acidification and multiple interactive stressors
- Investigations to identify species that are 1) particularly vulnerable, 2) less vulnerable, or 3) capable of rapid adaptation to the combined effects of acidification and associated stressors. Such investigations could help guide strategies to shift human uses of living marine resources to species that are less vulnerable or more resistant to projected changes in seawater chemistry.

Seven national research priorities were identified by participants in a workshop sponsored by NSF, NOAA, and USGS in April 2005 (Kleypas et al., 2006). These priorities, paraphrased here from the original report, are as follows:

- Determine the calcification response to elevated CO_2 in benthic and planktonic calcifiers
- Discriminate mechanisms of calcification and responses to changing seawater chemistry across taxonomic groups
- Determine the interactive effects of multiple variables that affect calcification and dissolution in organisms
- Establish clear links between laboratory experiments and the natural environment, by combining laboratory experiments with field studies
- Characterize diurnal and seasonal cycles in the carbonate system

- Monitor *in situ* calcification and dissolution of calcifiers, with better characterization of key controls on biocalcification
- Incorporate ecological questions into observations and experiments, e.g., individual survivorship, population growth rate, community structure, and ecosystem function.

A subsequent workshop was convened at the Scripps Institution of Oceanography in October 2007 by the Ocean Carbon and Biogeochemistry Program with sponsorship from NSF, NOAA, NASA, and USGS. The purpose of the workshop was to further refine scoping for research investigations of ocean acidification. Important research themes were phrased as questions of importance (paraphrased here):

- What are the temporal and spatial scales of change in the carbon system of the global oceans and what are the impacts on biological communities and ecosystems?
- Will marine organisms adapt or evolve to tolerate elevated CO_2 and temperature? If so, how?
- How does elevated CO_2 influence calcification, respiration, reproduction, settlement and recruitment, and remineralization in marine organisms?
- What are the effects of high CO_2 on processes affecting ecosystem response and global feedbacks?

9. Implications for Marine Resource Managers

Projected changes in seawater pH and carbonate saturation, combined with increasing temperature and declining levels of dissolved oxygen, will require the attention of marine resource managers. Effective management requires that processes integrating science into decision-making be developed and implemented. Key management responses are likely to include:

- More conservative limits on commercial and recreational harvest to compensate for losses due to acidification and associated stressors
- Greater consideration of food web effects (e.g., consideration of the abundance and distribution of prey species) in setting harvest limits and establishing rebuilding and recovery plans
- Preservation of species diversity and genetic diversity to provide functional redundancy and to enhance the capacity for biological adaptation to changes in ocean chemistry
- Protection and restoration of essential habitat features and processes to compensate for habitat losses due to acidification and associated stressors
- Alleviation of other human-induced stressors (pollution, eutrophication, shoreline development, habitat modification) to the maximum extent possible to reduce the effects of multiple interactive stressors and the likelihood of non-linear dynamical responses

10. Conclusion

Carbon emissions are causing changes in seawater chemistry that are unprecedented in the modern era. Ultimately, carbon emissions must be curbed. At the same time, serious and sustained efforts must be made now to reduce risks associated with changing ocean chemistry. Effective strategies will 1) provide policy-relevant science regarding the effects of ocean acidification and associated stressors on marine organisms and the ecosystems they comprise; 2) implement policies that are reflective of this science and are sensitive to the rates and magnitudes of environmental change; and 3) adjust policies as new information becomes available. Substantial new funding directed to universities and federal agencies is required to support essential scientific investigations. Creation of a strategic national research and implementation plan constitutes a first important step that must be followed by federal investment that is sufficient to support the informational needs of this serious threat to social, economic, and ecological systems.

11. Biographical Sketch

Terrie Klinger is Associate Professor of Marine Affairs and Adjunct Associate Professor in the School of Aquatic and Fisheries Sciences at the University of Washington and an active researcher at UW's Friday Harbor Laboratories. She obtained an A.B. in Biology from the University of California, Berkeley in 1979, a M.Sc. in Botany from the University of British Columbia in 1984 and a Ph.D. in Biological Oceanography from Scripps Institution of Oceanography in 1989. Her research focuses on ecological and policy issues in nearshore areas of the Pacific Northwest and Gulf of Alaska. She serves as Chair of the Olympic Coast National Marine Sanctuary Advisory Council, is the Governor's representative to the Northwest Straits Commission, and is a member of San Juan County's Climate Change Task Force.

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