WRITTEN TESTIMONY OF
SCOTT C. DONEY, Ph.D.
WOODS HOLE OCEANOGRAPHIC INSTITUTION[1]

HEARING ON
The Federal Ocean Acidification Research and Monitoring Act: H.R. 4174

BEFORE THE
COMMITTEE ON SCIENCE AND TECHNOLOGY
SUBCOMMITTEE ON ENERGY AND ENVIRONMENT
UNITED STATES HOUSE OF REPRESENTATIVES

JUNE 5th, 2008

Introduction

Good morning Chairman Lampson, Ranking Member Inglis and members of the Subcommittee. Thank you for giving me the opportunity to speak with you today on ocean acidification and the proposed Federal Ocean Acidification Research and Monitoring Act, H.R. 4174. My name is Scott Doney, and I am a Senior Scientist at the Woods Hole Oceanographic Institution in Woods Hole MA. My research focuses on interactions among climate, the ocean and global carbon cycles, and marine ecosystems. I have published more than 110 peer-reviewed scientific journal articles and book chapters on these and related subjects. I serve on the U.S. Carbon Cycle Science Program (CCSP) Scientific Steering Group and the U.S. Community Climate System Model (CCSM) Scientific Steering Committee. Currently I am the chair of the U.S. Ocean Carbon and Climate Change (OCCC) Scientific Steering Group and the U.S. Ocean Carbon and Biogeochemistry (OCB) Scientific Steering Committee.

For today's hearing, you have asked me to discuss the strengths and weaknesses of the current interagency effort to monitor and research ocean acidification and to assess its potential impacts on marine organisms and marine ecosystems, and in addition, to provide recommendations for strengthening individual programs of the federal agencies participating in the interagency committees focusing on ocean issues.

Current Scientific Understanding

My comments on our state of knowledge about ocean acidification are based on a broad scientific consensus as represented in the current scientific literature and recent in scientific assessments compiled by the scientific community, in particular the United Kingdom Royal Society (Royal Society, 2005), the German Advisory Council on Global Change (WBGU) (Schuster et al., 2006), and a U.S. science workshop sponsored by the National Science Foundation, National Oceanic and Atmospheric Administration and the United States Geological Survey (Kleypas et al., 2006).

---

[1] The views expressed here do not necessarily represent those of the Woods Hole Oceanographic Institution

The current rapid rise in atmospheric carbon dioxide levels, due to our intensive burning of fossil fuels for energy, is fundamentally changing the chemistry of the sea, pushing surface waters toward more acidic conditions. Greater acidity slows the growth or even dissolves ocean plant and animal shells built from calcium carbonate, the same mineral as in chalk and limestone. Acidification thus threatens a wide-range of marine organisms, from microscopic plankton and shellfish to massive coral reefs, as well as the food webs that depend upon these shell-forming species. Rising CO_2 levels will also alter a host of other marine biological and geochemical processes, often in ways we do not yet understand. Ocean acidification is a critical issue for the 21st century impacting on the health of the ocean, the productivity of fisheries, and the conservation and preservation of unique marine environments such as coral reefs.

Over the last 250 years, atmospheric carbon dioxide (CO_2) increased by nearly 40%, from pre-industrial levels of about 280 ppmv (parts per million volume) to nearly 384 ppmv in 2007 (Solomon et al. 2007). This rate of increase, driven by human fossil fuel combustion and deforestation, is at least an order of magnitude faster than has occurred for millions of years, and the current concentration is higher than experienced on Earth for at least the last 800,000 years and likely the last several tens of millions of years (Doney and Schimel, 2007). About 1/3 of this excess, anthropogenic carbon dioxide dissolves in the ocean, where it forms carbonic acid and a series of dissociation products. The release of hydrogen ions from the breakdown of carbonic acid lowers the pH of seawater, shifting the normally somewhat alkaline seawater (surface pH about 8.2) toward more acidic conditions. As important for many organisms is the simultaneous reduction in carbonate ion concentration, which is used in the construction of calcium carbonate ($CaCO_3$) shells. Ocean acidification is a predictable consequence of rising atmospheric CO_2 and does not suffer from uncertainties associated with climate change forecasts. Absorption of anthropogenic CO_2, reduced pH, and lower calcium carbonate saturation in surface waters, where the bulk of oceanic production occurs, are well-verified from models, hydrographic surveys and time series data (Feely et al 2004; Orr et al 2005).

Since preindustrial times, the average ocean surface water pH has fallen by about 0.1 units, from about 8.21 to 8.10 (Royal Society, 2005), and is expected to decrease a further 0.3-0.4 pH units (Orr et al., 2005) if atmospheric CO_2 concentrations reach 800 ppmv (the projected end-of-century concentration according to the Intergovernmental Panel on Climate Change (IPCC) business as usual emission scenario; Solomon et al. 2007). The most sensitive areas may be the subpolar North Pacific, the Southern Ocean, and along the Pacific continental shelf and margin where waters are already near or at corrosive levels for some carbonate shells (Feely et al., 2008). The problem of ocean acidification will be with us for a long time because it takes centuries to thousands of years for natural processes, primarily mixing into the deep-sea and increased dissolution of marine carbonate sediments, to remove excess carbon dioxide from the air.

Ocean acidification appears to have a significant, and often negative impact on many ocean plant and animal species. The magnitude and even the sign of the biological effects, however, differ from organism group to group and on the specific biological processes involved. Rising atmospheric CO_2 alters seawater chemistry in several different ways---reducing pH, increasing the partial pressure of dissolved CO_2 gas (pCO_2), increasing total dissolved inorganic carbon, and reducing carbonate ion and the saturation state of calcium carbonate minerals. Because of the reduction in calcium carbonate saturation state, much of the research emphasis has been on shell-forming plants and animals that use calcium carbonate including some plankton (coccolithophorids, foramaniferia, and pteropods), benthic mollusks (clams, oysters and mussels), echinoderms (sea urchins), corals and coralline algae. Laboratory experiments show that ocean acidification and changes in ocean carbonate chemistry directly harms many of these calcifying species by reducing shell formation, slowing growth rates and hindering reproduction (Fabry et al., 2008a). The degree of sensitivity varies among species, however, and some organisms may show enhanced calcification at CO_2 levels projected to occur over the 21st century (Iglesias-Rodríguez et al., 2008). However, calcification-CO_2 response studies exist for a limited number of species in many calcifying groups, and currently, we lack sufficient understanding of calcification mechanisms to explain species-specific differences observed in manipulative experiments.

The consequences of acidification will extend well beyond the fate of any particular marine species. Acidification impacts on processes fundamental to the overall structure and function of marine ecosystems. Any significant changes could have far reaching impacts for the future of ocean food-webs. Many marine animals prey on calcifying organisms or utilize their skeletons for habitat. Tropical corals are the backdrop for rich and diverse reef environments, and many fish species would disappear along with the corals. Others such as clams, scallops, oysters and sea urchins are important sources of seafood. Less familiar are the many shell-forming planktonic organisms, including plants like coccolithophores and marine snails called pteropods, which are an important food source for salmon and whales. Recent discoveries indicate the presence of extensive deep-water coral reefs around the edge of continents and on seamounts, which may decline before we fully understand their contribution as a habitat for fish. Some preliminary experiments suggest that larval and juvenile fish may also be at risk.

Human and Economic Dimensions of Ocean Acidification

Ocean acidification will also impacts the millions of people that depend on its food and other resources for their livelihoods. Fish and marine organisms provided, on average, 15.5% of the world’s protein in 2003 (FAO, 2007); losses of crustaceans, bivalves, their predators, and their habitat (in the case of reef-associated fish communities) would particularly injure societies that depend heavily on consumption, export, and tourism of marine resources. Reef losses would also expose low-lying settlements and biologically diverse regions to storm and wave damage, multiplying economic hardships (Anderson et al., 2006).

U.S. commercial fisheries depend on calcifying species and their predators, making economic effects from ocean acidification a likelihood over the next several decades. Acidification effects likely will be most directly felt on mollusk fisheries (e.g., clams, scallops, oysters and mussels), which provide 18% of total revenue (Figure 1, red tones). Crustaceans (e.g., lobsters, crabs, shrimp) may also be sensitive and contribute an additional 32% of total revenue. The possible indirect impacts through reduced food supply for commercial fish species is not well understood yet. For scale, in 2006 the total landing value (what is paid for a boat's catch at the dock) of the U.S. commercial fisheries was about $4 billion, and subsequent seafood processing, wholesale and retail activities added a net $35.1 billion to the gross national product (Andrews et al. 2007). Domestic commercial marine fisheries directly support a larger number of jobs in the fishing fleet, the exact number not well reported because many fishers are self-employed; wholesaling and seafood processing generates an additional nearly 70,000 jobs nationwide; including seafood retailing and food services expands that number substantially. Meanwhile, U.S. recreational saltwater fishing generated $12 billion of direct, indirect, and induced income (Steinback et al., 2004) and supported 350,000 jobs in 2004, many of them related to recreational boat sales and maintanence.

Scientific Knowledge Gaps and Future Research Directions

The U.S. research community has recently hosted two major scientific meetings to identify knowledge gaps and discuss future research needs in ocean acidification. The first meeting of 60 experts in the field was held in 2005 in St. Petersburg FL and sponsored by National Science Foundation (NSF), National Oceanic and Atmospheric Administration (NOAA) and the United States Geological Survey (USGS); the workshop developed a consensus set of recommendations related to ocean acidification and calcifying organisms (Kleypas et al., 2006). Building on that report, the U.S. Ocean Carbon and Biogeochemistry (OCB) Program (http://us-ocb.org/), supported NSF, NASA, and NOAA, hosted a planning workshop for 90 U.S. and international ocean scientists in La Jolla, CA in the Fall of 2007. The recommendations from the OCB workshop were similar to those of the St. Petersburg meeting but extended as well more broadly to acidification impacts on non-calcifying organisms and ocean biogeochemistry (Fabry et al., 2008b).

Major gaps exist in our current scientific understanding, limiting our ability to forecast the consequences of ocean acidification and hindering the development of adaptation approaches for marine resource managers. Thus far, most of the elevated CO_2 response studies on marine biota, whether for calcification, photosynthesis or some other physiological measure, have been short-term laboratory or mesocosm experiments ranging in length from hours to weeks. Chronic exposure to increased CO_2 may have complex effects on the growth and reproductive success of calcareous and non-calcareous plants and animals and could induce possible adaptations that are not observed in short term experiments. Our present understanding also stems largely from experiments on individual organisms or a species in isolation; consequently, the response of populations and communities to more realistic gradual changes is largely unknown.

Other aspects of ocean biogeochemistry may be strongly influenced by rising CO_2 levels. Recent experiments with one of the most abundant types of phytoplankton, *Synechococcus,* showed significantly elevated photosynthesis rates under warmer, high CO_2 conditions. Elevated CO_2 also enhanced nitrogen fixation rates (production of biologically useful nutrients from dissolved nitrogen gas) for a key tropical marine cyanobacteria, which would in effect fertilize the surface ocean and offset predicted reductions in tropical biological production due to climate warming and stratification. Further, a major but underappreciated consequence of ocean acidification will be broad alterations of inorganic and organic seawater chemistry beyond the carbonate system. Acidification will affect the biogeochemical dynamics of calcium carbonate, organic carbon, nitrogen, and phosphorus in the ocean as well as the seawater chemical speciation of trace metals, trace elements and dissolved organic matter.

A fully-integrated research program with in-water and remote sensing observing systems on multiple-scales, laboratory, mesocosm (large volumes of seawater either in tanks or plastic bags), and field process studies, and modeling approaches is required to provide policymakers with informed management strategies that address how humans might best mitigate or adapt to these long-term changes. This program should emphasize how changes in the metabolic processes at the cellular level will be manifested within the ecosystem or community structure, and how they will influence future climate feedbacks. A program should include the following components:

- Systematic monitoring system with high resolution measurements in time and space of atmospheric and surface water carbon dioxide partial pressure (pCO2), total dissolved inorganic carbon, alkalinity, and pH to validate model predictions and provide the foundations for interpreting the impacts of acidification on ecosystems;

- In regions projected to undergo substantial changes in carbonate chemistry, tracking of abundances and depth distributions of key calcifying and non-calcifying species at appropriate temporal and spatial scales to be able to detect possible shifts and distinguish between natural variability and anthropogenic forced changes;

- Standardized protocols and data reporting guidelines for carbonate system perturbation and calcification experiments;

- Manipulative laboratory experiments to quantify physiological responses including calcification and dissolution, photosynthesis, respiration, and other sensitive indices useful in predicting CO_2 tolerance of ecologically and economically important species;

- New approaches to investigate address long-term subtle changes that more realistically simulate natural conditions;

- Manipulative mesocosm and field experiments to investigate community and ecosystem responses (i.e., shifts in species composition, food web structure, biogeochemical cycling and feedback mechanisms) to elevated CO_2 and potential interactions with nutrients, light and other environmental variables;

- Integrated modeling approach to determine the likely implications of ocean acidification processes on marine ecosystems and fisheries including nested models of biogeochemical processes and higher trophic-level responses to address ecosystem-wide dynamics such as competition, predation, reproduction, migration, and spatial population structure;

- Robust and cost effective methods for measuring pH, pCO_2, and dissolved total alkalinity on moored buoys, ships of opportunity, and research vessels, floats and gliders;

- Studies on the human dimensions of ocean acidification including the socio-economic impacts due to damaged fisheries and coral reefs;

- Assessment of potential adaptation strategies needed by resource managers including reducing other human stresses (over-fishing, habitat destruction, pollution) to increase ecosystem resiliency as well as local-scale mitigation efforts.

Current National Research Effort on Ocean Acidification

Over the last several years, a growing U.S. research effort on ocean acidification has emerged. The research is supported by several federal science agencies and builds from two major oceanographic research programs one on ocean biogeochemistry, the U.S. Joint Global Ocean Flux Study (JGOFS; http://www1.whoi.edu/), which ran from the late 1980s through the mid-2000s, and one of marine plankton ecology, U.S. Global Ocean Ecosystems Dynamics (GLOBEC; www.usglobec.org), which is in it's concluding synthesis phase. Each of the federal science agencies involved brings a specific approach and research emphasis to the problem of ocean acidification.

The National Oceanic and Atmospheric Administration (NOAA) supports observational networks for ocean CO_2, pH and seawater carbonate system through a combination research ship based surveys (CLIVAR/CO_2 Repeat Hydrography Program; ushydro.ucsd.edu) and autonomous instruments on volunteer merchant vessels and moorings (http://www.aoml.noaa.gov/ocd/gcc/index.php). NOAA also is involved in biological impact assessment of acidification on corals and coral reefs and more recently fish and invertebrates. Most of NOAA funding supports scientists internal to NOAA, though there is some extramural funding of university researcher through the Climate Program Office and Sea Grant.

The National Science Foundation (NSF) supports unsolicited, hypothesis driven research on a wide range of relevant topics, from ocean chemistry and physics to organism biology and genomics. NSF and NASA jointly fund, along with NOAA, the CLIVAR/CO_2 Repeat Hydrography Program, which is directly documenting the decrease in ocean pH and changes in seawater carbonate chemistry. NSF has also supported the two longest running, continuous ocean carbon time-series, one off of Hawaii (http://hahana.soest.hawaii.edu/hot/hot_jgofs.html) and the other off of Bermuda, (http://bats.bios.edu). These sustained time-series were begun in 1988 under the JGOFS program and are key elements in directly demonstrating acidification trends. All NSF funding is extramural to the university academic community. As the only non-mission science agency, NSF has built in flexibility to adapt rapidly to new ideas as they arise from the research community and to fund higher risk, discovery driven investigations.

The National Aeronautics and Space Administration supports satellite and airborne remote sensing, ship-based process studies and field validation and numerical modeling relevant to ocean ecology and biogeochemistry. Much of the research is extramural and hypothesis driven. Satellite ocean color data from NASA's MODIS sensor and from GeoEYE and NASA's Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) (http://oceancolor.gsfc.nasa.gov/) have been used to characterize the global distributions calcareous plankton and coral reefs. NASA will also launch the Orbiting Carbon Observatory (OCO; http://oco.jpl.nasa.gov) this December, a 2- year exploratory mission to measure the vertical average atmospheric CO_2 concentration; this data can be combined with numerical models to estimate global patterns of the exchange of carbon dioxide from the ocean and atmosphere. Much of the NASA funded ocean ecology and biogeochemistry research is relevant to ocean acidification, and the funding specifically focused on acidification it is expected to grow in the future.

The Department of Energy (DOE) does not have an active ocean biogeochemical research program at the moment; in the past, it has supported relevant work on measuring and modeling ocean CO2 uptake, methods of deliberate ocean carbon sequestration, and ocean environmental genomics. The United States Geological Survey (USGS) co-sponsored a recent major ocean acidification workshop and report (Kleypas et al., 2006, has expertise on ocean carbonate systems and coastal ecosystems, and is supporting currently a limited research effort on acidification effects on coral reefs. Other federal science agencies with potential interest and expertise relevant to the acidification problem and its biological repercussions include the National Park Service, US Fish and Wildlife and the Environmental Protection Agency.

Strengths and Weaknesses of Present Interagency Effort

Despite some prominent successes, the present national investment in ocean acidification research is inadequate to address the research challenges described above and is not creating the required comprehensive research program integrating the chemical, biological and human dimension aspects of the acidification problem. There are issues involving the direction and funding level for both basic science, which provides information on the extent of ocean acidification, and applied science, which addresses adaptation strategies and solutions. Research and training go hand in hand, and more resources need to be devoted to undergraduate and graduate student training to ensure and strong scientific base for the future. Further, basic science efforts within the U.S. are often poorly connected with stakeholders and more applied research targeting coral reef and fisheries management and conservation. As a result, the U.S. research community is falling behind our European and Japanese colleagues, who are already moving forward on coordinated ocean acidification initiatives.

The current funding level for ocean acidification research does not support the deployment of sufficient ocean monitoring capabilities, particularly in coastal waters where economically important ecosystems are at risk. New findings just released last week in Science magazine (Feely et al., 2008) of corrosive, acidified ocean waters on the continental shelf along the US west coast indicate that acidification is a problem we face now, not decades in the future. But these results from the first systematic survey of seawater CO_2 and acidification in North American coastal waters also highlight the difficulties in monitoring ocean chemistry from slow moving and expensive ships. New robust chemical sensor technologies exist or are being developed, and an ocean acidification observing system needs to be deployed combining instrumented autonomous platforms (moorings, gliders, floats) supported by shipboard surveys and process studies.

The NSF supported ocean carbon time-series stations at Hawaii and Bermuda are pivotal to the US and international research community, the ocean equivalent of the iconic Mauna Loa atmospheric CO_2 record. But such long records over time, critical for identifying trends due anthropogenic CO_2 and acidification, are the exception not the rule. With our present funding mechanisms, it is difficult to maintain and support long-term, sustained time-series. Each 3-5 year funding cycle, the principal investigators need to create a new scientific justification for making continued measurements when in fact the unique value of time-series is their continuity over time, the value growing dramatically as the records extend over multiple decades (and funding cycles). The research community continues to struggle with simply maintaining current capabilities, and few new time-series are being established in different ocean environments.

In a similar vein, satellite measurements provide an unprecedented view of the temporal variations in ocean ecology. The ocean is vast, and the limited number of research ships move at about the speed of a bicycle, too slow to map the ocean routinely on ocean basin to global scales. By contrast, a satellite can observe the entire globe, at least the cloud free areas, in a few days. The detection of gradual trends such as those due to ocean acidification is challenging. Currently remote sensing can be used to estimate a number of biological and chemical properties of the ocean (e.g., particulate calcite, pCO2) relevant to understanding the impacts of an acidifying ocean on ocean ecology and chemistry. Finding trends in these records requires long, coherent and internally consistent, high-quality global time series. Potential gaps in data coverage between satellite missions are particular worrisome; each sensor has its own unique calibration issues, and without overlap of missions in orbit, it is often impossible to construct a climate quality time record the extends over multiple missions. At present, the on-going availability of high-quality, climate data records is not assured during the transition of many satellite ocean measurements from NASA research to the NOAA/DOD operational NPOESS program. For example, the present NASA satellite ocean color sensors, needed to determine ocean plankto, are nearing the end of their service life, and the replacement sensors on NPOESS may not be adequate for the climate community. Further, refocusing of NASA priorities away from earth science may dramatically limit or full preclude new ocean satellite missions need to characterize ocean biological dynamics.

US ocean acidification research is also limited, at present, by the size and scope of potential field research projects. In particular, the current funding environment does not encourage the next generation of mesocosm (large enclosed tanks or floating bags of water) and ecosystem-scale field experiments where scientists manipulate environmental conditions (e.g., CO_2, pH) and then examine how ocean biology changes. Many of the major unresolved questions concerning ocean acidification involve impacts on scales too large to test in the laboratory and on communities of organisms and species. The infrastructure and logistics for manipulative experiments is costly, but the scientific payoff can be substantial, and for some problems manipulation of the ecosystem provides new scientific insights that are not easily attained in other ways. Deliberate ocean iron release experiments are one such example. European scientists have made considerable headway on ocean acidification using a dedicated mesocosm facility for water-column plankton studies, and design studies are underway for manipulative coral reef acidification experiments, similar in concept to terrestrial Free Air Carbon Experiment (FACE) system used to study CO_2 fertilization effects on terrestrial grasses, shrubs and trees. The University of Washington is moving forward, with state and private foundation support, on plans for an ocean mesocosm system, which could be expanded into a facility broadly available to the US research community.

There are also a number of issues with the coordination and management across science agencies. Interagency coordination on US ocean acidification research occurs via several related pathways involving both program managers from the federal science agencies and federal and university scientists. The US Carbon Cycle Science Program (CCSP) is an interagency partnership (http://www.carboncyclescience.gov/) focused broadly on the global carbon cycle in the ocean, on land, and in the atmosphere and the interactions with climate. The CCSP is part of the US Climate Change Science Program, and it has an Interagency Working Group (agency representatives from NOAA, NASA, NSF, DOC, USGS and a number of other, more terrestrially oriented agencies) and a Scientific Steering Group. The Carbon Cycle Science Program initiated an ocean research program, the Ocean Carbon and Climate Change (OCCC) Program, focused on monitoring the ocean carbon system and predicting its future behavior.

A key issue with regards to ocean acidification is that the Carbon Cycle Science Program covers only a portion of the ocean acidification problem, namely the controls on the oceanic uptake of CO_2, resulting changes in seawater chemistry and ocean mechanisms that could damp or accelerate climate change by altering atmospheric CO_2 levels. Key aspects of the acidification problem on ecological and socio-economic impacts extend well beyond the purview of the Carbon Cycle Science Program, however. While there are elements of the US Climate Change Science Program that could address ecological research and coordination needs on ocean acidification, the interactions have been minimal and disjoint to date reflecting the conflicting demands of a Program covering such a wide research domain and not focused specifically on the ocean.

There is also an existing, informal interagency effort on ocean biogeochemistry and ocean acidification, the Ocean Carbon and Biogeochemistry (OCB) Program (http://us-ocb.org/), which is supported by federal program managers at the NSF, NASA, and NOAA and assisted by input from a scientific steering committee consisting of academic and government scientists. The OCB Program encompasses the scientific direction of the OCCC program and also expands into ocean ecology to the degree that it interactions with biogeochemical cycling. The OCB and OCCC scientific steering groups overlap in membership and meet jointly. The OCB has taken the lead on organizing a recent major US ocean acidification workshop last Fall in La Jolla CA (Kleypas et al., 2008b), and is also working to ensure the appropriate international linkages with emerging and existing ocean acidification programs supported by the European Union, Australia and Japan. The informal interactions facilitated by OCB are working well but do not cover the full scope of acidification research, for example the more fisheries and coral reef oriented work currently supported internally within NOAA or socioeconomic components of the problem.

Recommendations on the Federal Ocean Acidification Research and Monitoring Act

The Federal Ocean Acidification Research and Monitoring Act, H.R. 4174, is an important step toward a comprehensive U.S. ocean research program. The proposed funding level ramping to $30 million in FY2012 will greatly enhance U.S. research capabilities. But even this level may fall short of true needs, which are estimated at closer to $50-55 million a year based on recent scientific community-wide planning efforts. To put this in context, one can compare against the funding levels of prior major oceanographic research programs. The US JGOFS and US GLOBEC programs in the 1990s involved large-scale field research on ocean biogeochemistry and ecology, similar to what is envisioned in a new ocean acidification program. In the late 1990s the NSF component of those two programs totaled about $24 million a year. Adding the contributions from NOAA, NASA and DOE approximately doubled the total funding to about $40-45 million per year in late 1990s dollars unadjusted for inflation and the rising ship operation costs. This cost estimate does not consider that a comprehensive acidification program will include additional research components on coral reef, fisheries, and human dimensions.

- The total authorization for FORAM (H.R 4174) should be increased to $50-55 million per year, a reasonable minimum to conduct the required basic and applied research and deliver those results in a timely fashion to stakeholders, resource managers and policymakers.

The US scientific community is well poised to take advantage of increased funding on ocean acidification. As demonstrated by the consensus recommendations from two recent major US ocean acidification science workshops (Kleypas et al., 2006; Fabry et al., 2008b), a roadmap for a coherent acidification program is in place and the community could move quickly toward implementing these research plans as increased funding becomes available. Forward progress on an expanded US ocean acidification research program should not be delayed waiting for the completion of the proposed National Academy of Sciences study on ocean acidification research priorities.

- The ramp-up in research funding in H.R. 4174 should be accelerated in order to more quickly get needed information into the hands of stakeholders and decision makers.

Other recommendations on funding approaches for ocean acidification include:

- Funds should be directly authorized to the major ocean science agencies (NSF and NASA), rather than distributed to NOAA; this would streamline planning, speed research progress, and take better advantage of the unique capabilities of the other agencies.

- A substantial portion of the authorized funding should be not just competitive but also extramural, to harness the tremendous capacity of our university academic research community – considering the scope of this problem, we need to bring all available resources to bear on developing the science quickly and efficiently.

The structure of the ocean acidification research program should remain adaptive and encourage exploration of a broad range of scientific areas. Ocean acidification is a new area of research, and many surprises remain ahead. This is illustrated by dramatic findings announced just in the last few weeks on accelerated acidification along the US west coast (Feely et al., 2008) and increased calcification by some phytoplankton under high CO_2, counter to our expectations about an increasing corrosive ocean (Iglesias-Rodriguez et al., 2008). Ocean acidification research is at present multi-faceted and fast-moving, and marine plants and animals and ocean biogeochemical cycle are affected by more than simply reduced seawater pH. There is much that we do not understand as yet about ocean acidification and the multiple pathways by which acidification and rising CO_2 will alter the marine environment.

- The current definition of "ocean acidification" in the bill should be expanded from simply reduced pH to incorporate the full suite of changes in ocean chemistry arising from increased carbon dioxide.
- The scope of the ocean acidification research program should leave wide latitude for the types of exploratory and discovery-based science investigations generally supported by the NSF, NASA and the extramural components of NOAA (e.g., NOAA Climate Program Office).

Strong interagency cooperation and coordination is critical to leverage the diverse expertise and research infrastructure of the individual federal science agencies, which tie into different parts of the US ocean science community. But this may be best accomplished through successful existing structures rather than by creating a new interagency committee. These include the National Ocean Partnership Program (NOPP; http://www.nopp.org) and the NSTC Joint Subcommittee on Ocean Science and Technology (JSOST; http://ocean.ceq.gov/about/jsost.html). There is also considerable merit to more informal interagency partnerships, such as those that supported the US Joint Global Ocean Flux Study and that are now supporting the US Ocean Carbon and Biogeochemistry Program. A strong and on-going dialog needs to be maintained between federal agency program managers and the scientific community, consisting of both federal and university researchers, on the planning, implementation and synthesis of ocean acidification research. This can be accomplished through a variety of mechanisms including scientific steering groups and community workshops. Finally, ocean acidification is a global problem, and the US and international research communities should work closely to increase the pace of discovery and the development of adaptation strategies.

- The bill should support a strong, interagency consultative process on the science of ocean acidification with substantial and ongoing input from the scientific community.

- The US ocean acidification program should establish strong ties with similar international research programs and develop mechanisms for US researchers to participate freely in international research activities.

Selected References

Anderson, P., et al. 2006. *Climate Change Futures: Health, Ecological, and Economic Dimensions*. The Center for Health and the Global Environment, Harvard Medical School. 136 pp.

Andrews, R., D. Bullock, R. Curtis, L. Dolinger Few, et al., 2007. *Fisheries of the United States, 2006*. National Marine Fisheries Service Office of Science and Technology, Fisheries Statistics Division, National Oceanographic and Atmospheric Administration.

Doney SC, Schimel DS. 2007. Carbon and climate system coupling on timescales from the Precambrian to the Anthropocene. *Annual Review of Environment and Resources* 32: 31-66

Doney, S.C. and H.W. Ducklow, 2006: A decade of synthesis and modeling in the U.S. Joint Global Ocean Flux Study, *Deep-Sea Res. II,* **53**(5-7), 451-458.

Fabry, V. J., B. A. Seibel, R. A. Feely, and J. C. Orr, 2008a. Impacts of ocean acidification on marine fauna and ecosystem processes. ICES *J. Mar Science*. 65, 414-432.

Fabry, V.J., C. Langdon, W.M. Balch, A.G. Dickson, R.A. Feely, B. Hales, D.A. Hutchins, J.A. Kleypas, and C.L. Sabine, 2008b: Ocean acidification's on marine ecosystems and biogeochemistry, *Eos, Trans. Americ. Geophys. Union*, 89, 143-144. (for full meeting report see also http://www.whoi.edu/sites/OceanAcidificationMeeting)

Feely, R.A., C.L. Sabine, K. Lee, W. Berelson, J. Kleypas, et al. 2004. Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science* 305:362-6

Feely, R.A., C.L. Sabine, J.M. Hernandez-Ayon, D. Ianson, and B. Hales, 2008. Evidence for upwelling of corrosive "acidified" water onto the continental shelf, *ScienceExpress*, doi:10.1126/science.1155676

Food and Agriculture Organization (FAO) of the United Nations, 2007. *The state of world fisheries and aquaculture, 2006.* Rome. FAO Fisheries and Aquaculture Department. 180 pp.

Iglesias-Rodríguez, M D., P R Halloran, R. E. M. Rickaby, I. R. Hall, E. Colmenero-Hidalgo, J. R. Gittins, D. R. H. Green, T. Tyrrell, S. J. Gibbs, P. von Dassow, E. Rehm, E. V. Armbrust, and K. P. Boessenkool. 2008. Phytoplankton calcification in a high CO_2 world. *Science*.320: 336-339.

Kleypas JA, Feely RA, Fabry VJ, Langdon C, Sabine CL, Robbins LL. 2006. Impacts of ocean acidification on coral reefs and other marine calcifiers: A guide for future research. Report of a workshop held 18-20 April, 2005, St. Petersburg, FL, sponsored by NSF, NOAA, and the U.S. Geological Survey

National Research Council, 1999: *Global Ocean Science-Toward an Integrated Approach*, Ocean Studies Board and Commission on Geosciences, Environment, and Resources, National Research Council, National Academy Press, Washington, D.C., 165pp.

Orr, J.C., V.J. Fabry, O. Aumont et al. (2005) Anthropogenic ocean acidification over the twenty-first century and its impact on marine calcifying organisms, Nature, 437, 681-686, doi:10.1038/nature04095.

Royal Society (2005) Ocean acidification due to increasing atmospheric carbon dioxide, *Policy Document 12/05*, The Royal Society.

Schubert, R., H.-J. Schellnhuber, N. Buchmann, A. Epiney et al. 2006. The future oceans-warming up, rising high, turning sour, German Advisory Council on Global Change (WBGU) Special Report, ISBN 3-936191-14-X, http://www.wbgu.de, Berlin, Germany, 110pp.

Solomon S, Qin D, Manning M, Chen Z, Marquis M, et al. 2007. *Climate Change 2007: The Physical Science Basis: Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*. New York: Cambridge Univ. Press.

Steinback, S., B. Gentner, J. Castle, 2004. *The Economic Importance of Marine Angler Expenditures in the United States*. NOAA Professional Paper NMFS 2. Scientific Publications Office, National Marine Fisheries Service, NOAA, 76 Sand Point Way NE, Seattle, WA 98115. 184 pp.