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EFFECTS OF CLIMATE CHANGE AND OCEAN ACIDIFICATION ON LIVING MARINE ORGANISMS

HEARING

BEFORE THE

SUBCOMMITTEE ON OCEANS, ATMOSPHERE, FISHERIES, AND COAST GUARD

OF THE

COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION

UNITED STATES SENATE

ONE HUNDRED TENTH CONGRESS

FIRST SESSION

MAY 10, 2007

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EFFECTS OF CLIMATE CHANGE AND OCEAN ACIDIFICATION ON LIVING MARINE ORGANISMS

THURSDAY, MAY 10, 2007

U.S. SENATE,
SUBCOMMITTEE ON OCEANS, ATMOSPHERE, FISHERIES, AND COAST GUARD,
COMMITTEE ON COMMERCE, SCIENCE, AND TRANSPORTATION,
Washington, DC.

The Subcommittee met, pursuant to notice, at 10:22 a.m. in room SR–253, Russell Senate Office Building, Hon. Maria Cantwell, Chairman of the Subcommittee, presiding.

OPENING STATEMENT OF HON. MARIA CANTWELL, U.S. SENATOR FROM WASHINGTON

Senator CANTWELL. Good morning. The Senate Committee on Commerce, Science, and Transportation and the Oceans, Atmosphere, Fisheries, and Coast Guard Subcommittee hearing will come to order. I thank the witnesses for their indulgence. The Senate had a vote and some of my colleagues I am sure will be joining us shortly. But I thought that we should go ahead and get started. I thank you very much for being here.

I know that we have a distinguished set of witnesses: Dr. Scott "DONN-ey," is that right?

Dr. DONEY. "DOE-ney."

Senator CANTWELL. "DOE-ney." Thank you very much.

Dr. Richard Feely; is that correct? I should know that, given your presence in the Pacific Northwest. Dr. David Conover, Dr. Lara Hansen, Dr. Gordon Kruse, and Admiral James Watkins. Thank you for returning to the Committee and for your steadfast involvement in this issue.

I know that some of you have PowerPoint presentations and we will try to accommodate you this morning on that and give you a few extra minutes and, as I said, as my colleagues arrive we will also give them time to make opening statements.

I would like to again welcome each of you to this important Committee to talk about the impact of climate change and ocean acidification on our living marine resources. Today you represent some of the top experts in the field of ocean and climate change and I would like to thank each of you for your testimony and for your leadership in this area.

Since the start of the Industrial Revolution 200 years ago, humans have released over 1.5 trillion tons of carbon dioxide into the atmosphere and only now are we beginning to understand the implications of this. When scientists first started raising questions about our carbon dioxide emissions in the 1950s, very little was known about the possible consequences. Some predicted that carbon dioxide would accumulate in the atmosphere. Others predicted it would be absorbed by the world's oceans. Today we know that both of those were correct.

Human-caused emissions have increased the global atmospheric carbon dioxide concentration by 35 percent. In addition, over half a trillion tons of carbon dioxide have been absorbed by our oceans. We are already seeing the impacts of this on our oceans and our coastal ecosystems. If we continue with business as usual, the ecological, social, and economic consequences are likely to be severe.

After extensive scientific research, climate scientists now know that global warming is happening and it is happening because of human use of fossil fuel. We are seeing more results of global warming every day. Year after year, our polar ice caps are receding, glaciers are shrinking rapidly, even disappearing, and, to give one example from my home state, the Intergovernmental Panel on Climate Change recently reported that the mountain snow pack that feeds the Columbia River system is shrinking away, producing less and less water for the rivers every year.

While these easy-to-see impacts of global warming are highly disturbing, we are here today to examine the impacts that are not quite as visible, but yet just as severe: those that occur beneath the surface of our oceans. The impact of climate change on coastal communities from sea level rise and increased storm intensity have been the focus of much attention. But climate change also poses risks to our Nation's multibillion dollar fishing industry. In fact, global warming could threaten the very integrity of our oceans' ecosystem, possibly wiping out more vulnerable ecosystems like coral reefs.

These are frightening possibilities, but very real ones. While it may not be easy to see the impacts of global warming in the ocean, it is vital that we examine it. If we wait until these problems are too painful or too obvious to ignore, it will be far too late. While carbon dioxide is accumulating in our atmosphere, it also is being absorbed by oceans, and approximately one-third of carbon dioxide emissions end up in the oceans.

For decades we assumed that the oceans would absorb these greenhouse gases to the benefit of our atmosphere, with no side effects for our seas. Emerging science now shows we were wrong. Thanks in no small part to the work of our panelists; we now know that the absorption of carbon dioxide actually changes the very chemistry of our oceans. Sea water becomes more acidic and begins to withhold the basic chemical building blocks needed by many marine organisms. Coral reefs, the rain forests of the sea, cannot build their skeletons, and in colder waters, scientists predict, more acidic oceans can dissolve the shells of tiny organisms that make up the base of the ocean's food chain.

When it comes to ocean acidification, we risk not just damaging the oceans' ecosystem; we are threatening its very foundation. The social and economic costs to the world's fisheries and fishery-dependent communities are incalculable. Managers at the State and local and regional levels must be able to anticipate and develop strategies to address these threats.

The danger of global climate change and ocean acidification can be illustrated with one example from my home state of Washington. Washington is home to a very important salmon population. Salmon are a $330 million industry in the Pacific Northwest and certainly a cultural icon. As I mentioned earlier, the global warming will continue to reduce the snowpack that feeds our rivers will continue to have impacts. As these waters become less, the waters will become warmer. Salmon rely on a predictable, steady flow for their survival.

Every coastal State can point to examples like these, and these examples are far too important to ignore. Both global warming and ocean acidification have the same cause and the same solution—we must reduce our emissions of carbon dioxide. If we fail to address the potential impact of global climate change and ocean acidification, we can be jeopardizing all we have fought so hard for on ocean conservation and the gains that have already been made. These are difficult words to hear, I think, but reflect a difficult reality.

Again, I want to thank all of you for joining us and for your hard work on this very important issue. We look forward to your testimony.

I know I have been joined by Senator Stevens, the Ranking Member of the full Committee, and I invite him to make any opening comment, and to note that Senator Snowe is unable to join us today because of a conflict, but is reviewing the testimony and will be very involved in any further steps and will look forward to seeing the testimony of the witnesses. But I thank Senator Stevens for his participation and his presence here this morning.

[The prepared statement of Senator Snowe follows:]

PREPARED STATEMENT OF HON. OLYMPIA J. SNOWE, U.S. SENATOR FROM MAINE

Thank you, Madam Chair, for calling this critical hearing to discuss how climate change may affect the future of our oceans and their living marine resources. I am pleased that this committee is so actively investigating the burgeoning issue of ocean acidification—a topic that in just a few short years has developed from a relatively unknown theory into what is potentially one of the most disconcerting aspects of ocean-related climate science.

Lost in much of the discussion of climate change has been its potential impacts on the oceans' corals, fish, and other species. Recent research—much of it conducted by members of our esteemed panel of witnesses—has indicated that as a direct result of the precipitous increase in carbon dioxide in our atmosphere, our oceans are warming and becoming more acidic. If we continue to allow emissions of carbon dioxide to increase, we could see drastic, worldwide impacts in our oceans, from species migration and coral bleaching to widespread extinctions.

The oceans drive much of our Nation's economy, as well as that of my home state of Maine. Throughout our state's history, stewardship of our marine resources has pervaded our maritime activities. Nowhere is this more evident than in our lobster fishery, which for generations has engaged in self-imposed, sustainable fishing practices. The result of that stewardship is a robust industry that landed over $270 million worth of lobster in 2006. Today, that fishery faces potential danger. Not from the activities of our lobstermen, but from the potential effects of global climate change.

In 1999, the lobstermen of Long Island Sound began pulling up pots full of dead lobster. According to a study by Connecticut's Sea Grant program, that fall, commercial landings from western Long Island Sound plummeted an astounding 99 percent from the previous year. Nearly three-quarters of the Sound's lobstermen lost all of their income. The study concluded that, "the physiology of the lobsters was severely stressed by sustained, hostile environmental conditions, driven by above average water temperatures." In other words, warming ocean temperatures created conditions that killed these lobsters and decimated the fishery.

The lobster industry's collapse in Long Island Sound may be a harbinger for other fisheries. Evidence is mounting that anthropogenic emissions of greenhouse gasses—carbon dioxide in particular—are disrupting the forces that drive our climate and in turn, our oceans. Approximately a third to a half of global manmade carbon dioxide emissions have already been absorbed into the world's oceans. This amount will double by 2050, and all indications are that this will increase the acidity of the oceans' surface and could initiate the largest change in pH to occur in as many as 200 *million years.* Clearly, the consequences of such a shift could be catastrophic. Which is why my colleague Senator Kerry and I introduced S. 485, the Global Warming Reduction Act of 2007. This legislation is the only introduced climate bill that specifically calls for research to address the vulnerability of marine organisms throughout the food chain to increased carbon dioxide emissions. It also requires an assessment of probability that such a change will cost us more than 40 percent of our coral reefs—delicate ecosystems that are especially vulnerable to both ocean acidification and warming.

And coral reefs are just as integral to the economy and heritage of tropical states such as Florida and Hawaii as fisheries are to Maine. In order to protect these resources, we must understand what is happening to them. The final report of the U.S. Commission on Ocean Policy, chaired by Admiral Watkins who is testifying before us today, calls for development and implementation of a sustained Integrated Ocean Observing System to provide the data necessary to understand the complex oceanic and atmospheric systems—including pH, temperature, salinity and the speed and direction of currents—that comprise our oceans. I know the scientists here today also support that initiative, and I support it as well.

In each of the past two Congresses, I have introduced a bill to authorize an Integrated Ocean Observing System and develop a national framework to oversee and our numerous, successful, independent regional observing systems. Twice this bill has passed the Senate unanimously, but failed to pass the House. I have introduced a new version of this bill—the Coastal and Ocean Observation Systems Act of 2007, S. 950—in the 110th Congress, with sixteen bi-partisan co-sponsors, and I am working closely with members from both chambers to ensure that this bill becomes law as soon as possible.

Mounting evidence linking carbon emissions to potentially devastating changes in the hydrology of our oceans compels us to act now to protect the future of the irreplaceable resources found beneath the waves. I will continue to do everything in my power to provide our scientists with the requisite tools to carry our their research and ensure that we prevent further damage to these vital ecosystems. I thank Doctors Feely, Conover, Doney, Kruse, and Hansen and Admiral Watkins for taking the time to engage in what I believe will be a fruitful and fascinating discussion, and I look forward to hearing all of your testimony.

Thank you, Madam Chair.

STATEMENT OF HON. TED STEVENS, U.S. SENATOR FROM ALASKA

Senator STEVENS. Thank you very much.

To maintain our sustainable fisheries, it is important that we try to understand how changes to the oceans' environment affect our fish stocks. Much of the focus on Capitol Hill and in the media is centered on how climate change will affect life on land through higher temperatures, storms, and sea levels. What many do not realize is that the oceans may change as well and, as the chairwoman has said, if the predictions are accurate these changes could have economic and serious consequences.

Warm ocean temperatures are causing widespread coral bleaching in the Caribbean. In Alaska some species are moving north. There is concern about how these changes will affect the fisheries off our shores—half the coastline of the United States is in Alaska.

We know very little about these changes. We do not know how much this change is due to natural variations and how much is manmade. In Alaska our fisheries have been impacted in the past due to natural variations in ocean temperature caused by the Pacific Decadal Oscillation shifts in ocean currents. Some fisheries in Alaska have flourished due to warmer temperatures. Others have seen temporary declines.

I am pleased to see these panelists here today, Madam Chairman. What we have been witnessing could have serious consequences for marine life and fisheries worldwide, and I know these panelists can help the Committee identify some of the current gaps in our knowledge. We need to make sure the Federal agencies have the resources in the right places to study ocean acidification and climate change.

I thank the panelists. I do particularly thank Dr. Gordon Kruse, who has traveled all the way from Juneau to participate in today's hearing. Dr. Kruse has studied fisheries in Alaska for decades, most recently serving as Chair of the Scientific and Statistical Committee of the North Pacific Fishery Management Council. Their Committee plays a vital role in what the Pew Commission has stated is the best managed fishery in the world, thanks to the science that Dr. Kruse and others have given us.

Let me welcome Admiral Watkins. It is always a pleasure to have him back because we have followed his thoughts on ocean policies for some time. I look forward to the testimony.

Thank you very much.

Senator CANTWELL. Thank you, Senator Stevens.

Senator Klobuchar?

STATEMENT OF HON. AMY KLOBUCHAR, U.S. SENATOR FROM MINNESOTA

Senator KLOBUCHAR. Thank you, Madam Chair. Thank you for all of you coming. I am the Senator from Minnesota. I am the only member of the Committee without an ocean. But I am pleased to be here, of course, because of the Great Lakes and how important that is to our way of life in Minnesota, with Lake Superior, as well as our economy in Minnesota. I will tell you that the lake levels in the Great Lakes continue to drop and we are seeing an impact on the economy.

We are also seeing an impact of climate change on our 10,000 lakes that we are so proud of in Minnesota. That is what our license plate says and it is something we are proud of. But we have fishermen who cannot put their icehouses out for a month. We have all kinds of issues that are coming up with our wetlands.

So I look forward to hearing from this panel and thank you for coming today.

Senator CANTWELL. With that, we will go ahead and get started with our witnesses. Mr. Doney, you are first. As I said, I think we are asking people if they could keep their comments to 5 minutes, knowing that some of you who have slide presentations might take a little longer just to get through that. But thank you very much for being here.

STATEMENT OF SCOTT C. DONEY, PH.D., SENIOR SCIENTIST, DEPARTMENT OF MARINE CHEMISTRY AND GEOCHEMISTRY, WOODS HOLE OCEANOGRAPHIC INSTITUTION

Dr. DONEY. Thank you. Good morning, Madam Chair, Ranking Member Stevens, and other members of the Subcommittee. My name is Scott Doney and I am a Senior Scientist at the Woods Hole Oceanographic Institution, and I want to thank you—for the opportunity to talk to you about ocean acidification and climate change.

There is a broad U.S. scientific consensus that human activities are increasing atmospheric carbon dioxide, altering our planet's climate and acidifying the ocean. Climate change and acidification will increasingly impact fisheries, coral reefs, coastal environments, and the important economic and ecosystem functions delivered by the ocean. We have an opportunity to limit the negative impacts of ocean acidification and climate change, but only if we take deliberate and immediate action.

Atmospheric carbon dioxide has increased by 35 percent over the last 2 centuries, mostly due to fossil fuel combustion. Carbon dioxide is a greenhouse gas that traps heat near the Earth's surface. Climate processes amplify the impact of elevated carbon dioxide and other greenhouse gases and lead to warming of the land and the ocean, melting of glaciers, retreat of sea ice, and rising sea level.

Global warming should really be called ocean warming, as more than 80 percent of the increased heat actually ends up in the ocean. Measurements show that ocean warming is extending from the surface down to a depth of at least 10,000 feet and over the last several decades there has been a retreat of Arctic sea ice by 15 to 20 percent over the summer and some models predict that we will have ice-free conditions in the Arctic by the year 2040.

But warming is not the only impact of carbon dioxide. Elevated carbon dioxide also alters ocean chemistry. The ocean absorbs about one-third of fossil fuel carbon emissions and once in the ocean carbon dioxide combines with water to form an acid, leading to more acidic conditions. The physical chemistry of this process is well known and well understood.

Climate change and ocean acidification are confirmed by real world observations and are supported by both models and theory. Unless greenhouse gas emissions are curbed, these trends will only accelerate over the next several decades. Atmospheric carbon dioxide is already higher than at any time in the last half million years and may double again in concentration by the end of this century.

Warming and acidification affect ocean plants and animals both directly and via changes in the ecosystems which they depend upon for food and habitat. Some broad trends can be identified. These include reduced biological productivity in low and mid latitudes, polar shifts in warm-water species, and declines in corals and other shell-forming plants and animals.

From historical data we know that commercially important species such as salmon are sensitive to climate-driven changes in the base of the ocean food chain. Of particular concern is if there are climatic tipping points in the future that may induce rapid and dramatic alterations in ocean ecosystems. My fellow panelists will discuss in more detail some of the changes we are already seeing and what we might expect to see in the future.

For fisheries, climate and acidification impacts will likely exacerbate other problems, including overfishing, pollution, excess nutrients, and habitat destruction. Marine life has survived large variations in the past, but the current rates of climate change and ocean acidification are much faster than experienced in most of geological history. The reality of climate change and ocean acidification is now clear. Less clear is the total extent of the repercussions that we face.

First and foremost, we need to control and reduce the emissions of carbon dioxide and other greenhouse gases that are the root of the problem.

Second, we need enhanced investment in an effort to monitor ocean changes, understand biological responses, and convey this information to stakeholders.

Third and finally, we need a comprehensive ocean management strategy that explicitly addresses the need to adapt to climate change and acidification that are now unavoidable.

Thank you for giving me this opportunity to address the Subcommittee and I look forward to your questions.

[The prepared statement of Dr. Doney follows:]

PREPARED STATEMENT OF SCOTT C. DONEY, PH.D., SENIOR SCIENTIST, DEPARTMENT OF MARINE CHEMISTRY AND GEOCHEMISTRY, WOODS HOLE OCEANOGRAPHIC INSTITUTION [1]

Introduction

Good morning Madame Chair, Ranking Member Snowe and members of the Subcommittee. Thank you for giving me the opportunity to speak with you today on global climate change, ocean acidification and the resulting impacts on fisheries and living marine resources. My name is Scott Doney, and I am a Senior Scientist at the Woods Hole Oceanographic Institution in Woods Hole, Massachusetts. My research focuses on interactions among climate, the ocean and global carbon cycles, and marine ecosystems. I have published more than 90 peer-reviewed scientific journal articles and book chapters on these and related subjects. I serve on the U.S. Carbon Cycle Science Program Scientific Steering Group and the U.S. Community Climate System Model Scientific Steering Committee, and I am Chair of the U.S. Ocean Carbon and Climate Change Scientific Steering Group and the U.S. Ocean Carbon and Biogeochemistry Scientific Steering Committee.

For today's hearing, you have asked me to discuss the mechanisms by which greenhouse gases impact the ocean, coastal environment, and living marine resources, gaps in our current scientific understanding, and implications for resource management including adaptation and mitigation strategies. My comments are based on a broad scientific consensus as represented in the current scientific literature and in community assessments such as the 2007 Intergovernmental Panel on Climate Change (IPCC) reports (IPCC, 2007a; 2007b; 2007c).

Over the past two centuries, human activities have resulted in dramatic increases in atmospheric carbon dioxide and other greenhouse gases. There is broad scientific consensus that these excess greenhouse gases are altering our planet's climate and acidifying the ocean. These findings are confirmed by real-world observations and supported by theory and numerical models. Climate change and acidification trends will accelerate over the next several decades unless there is deliberate action to curb greenhouse emissions. Rising atmospheric carbon dioxide and climate change produce upper-ocean warming, sea-ice retreat, sea-level rise, ocean acidification, altered freshwater distributions, and maybe even stronger storms.

Growing evidence suggests that these human-driven climate change and acidification will strongly impact ocean ecosystems as well. Further pressure will be put on living marine resources, such as fisheries and coral reefs that we depend upon for

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

food, tourism and other economic and aesthetic benefits. We have an opportunity now to limit the negative impact of climate change and acidification in the future. This will require a comprehensive ocean management strategy that incorporates scientific understanding of climate change and acidification from the start. This strategy will also require a balance between adaptation to climate change and acidification that are unavoidable, and mitigation to reduce the rise in greenhouse gases and resulting impacts.

Greenhouse Gases and Climate Change

At the most basic level, the balance between incoming sunlight and outgoing infrared radiation (*i.e.,* heat) determines Earth's climate. The greenhouse gas carbon dioxide (CO_2) plays a key role by absorbing infrared radiation and thus trapping heat near the Earth's surface much like a blanket. Other trace greenhouse gases such as methane (CH_4), nitrous oxide (N_2O), and chlorofluorocarbons (CFCs) are also important to warming, equivalent to about half of that from carbon dioxide, because molecule for molecule they absorb more infrared radiation than carbon dioxide. Other factors involved in human-driven climate change include aerosols and land vegetation.

Over the last two centuries, atmospheric carbon dioxide has increased by more than 30 percent, from 280 to 380 ppm (part per million) by 2007. The main source is fossil-fuel combustion with contributions from cement production, agriculture and deforestation. Many economic and climate models predict atmospheric carbon dioxide values as high as 700 to 1,000 ppm, about triple preindustrial levels, by the end of the twenty-first century. The Earth has not experienced carbon dioxide levels that high for the past several million years. Other trace greenhouse gas levels are growing as well due to land-use, agriculture and industrial practices. These greenhouse gases persist in the atmosphere for years to decades, meaning that they will remain and accumulate in the atmosphere, impacting the global climate for a long time to come. In contrast, aerosols in the lower atmosphere are removed on time-scales of a few days to weeks, and their climatic impacts, mostly cooling, are concentrated near their sources.

Greenhouse gases dominate over other human-driven climate perturbations, and the increased heating translates into changes in climate properties such as surface temperature, rainfall, sea-level and storm frequency and strength. The climate change resulting from an increase in greenhouse gases can be amplified by other climate processes. For example, ocean warming leads to a large retreat in Arctic sea-ice, which further strengthens warming because the dark water surface can then absorb more sunlight than the highly reflective ice. The largest unknowns at present arise from cloud dynamics. Numerical model climate projections for this century show global mean surface temperature increasing, with a range of +1.1 to 6.4° C (+2.0 to 11.5° F) above late 20th century levels. This large temperature range is somewhat misleading as a significant fraction of the variation depends on human behavior, specifically how much carbon dioxide and other gases we emit to the atmosphere in the future. The lowest temperature projections occur only when emissions are reduced sharply over the next few decades.

The largest projected temperature changes are concentrated over the continents and at higher latitudes during the winter season, but some level of warming will occur globally, over the ocean, and year-round. Sea-level is estimated to rise due to thermal warming and melting glaciers and ice sheets by an additional +0.18 to 0.59m (+0.6 to 1.9 feet) by 2,100. Many simulations suggest a general strengthening of the water cycle, with increased precipitation in the tropics and high latitudes, drier conditions in the subtropics, and an increased frequency of extreme droughts and floods. Other common features of a warmer climate are more El Niño-like conditions in the Equatorial Pacific, a melt back of polar sea-ice and glaciers, and a slowdown in the formation of ocean deep water at high latitudes.

The Changing Ocean Environment

Global warming should be called ocean warming, as more than 80 percent of the added heat resides in the ocean. Clear alterations to the ocean have already been detected from observations. The magnitude and patterns of these changes are consistent with an attribution to human activities and not explained by natural variability alone. Global average land and ocean surface temperatures increased at a rate of about 0.2° C/decade over the last few decades (Hansen *et al.,* 2006), and ocean temperatures down to 3,000 m (10,000 feet) depth are also on the rise. Averages rates of sea-level rise over the last several decades were 1.8±0.5 mm/y, with an even larger rate (3.1±0.7 mm/y) over the most recent decade. Higher precipitation rates are observed at mid to high latitude and lower rates in the tropics and subtropics. Corresponding changes have been measured in surface water salinities. One of the most striking trends is the decline in Arctic sea-ice extent, particularly over the summer. September Arctic ice-cover from 2002–2006 was 18 percent lower than pre-1980 ice-cover (*http://www.arctic.noaa.gov/detect/ice-seaice.shtml*), and some models predict near ice-free conditions by 2040. Recent studies of the Greenland ice sheet highlight an alarming increase in surface melting over the summer, and percolation of that melt water to the base of the ice sheet where the melt-water could lubricate ice flow and potentially greatly accelerate ice loss and sea-level rise. These new findings have not been full incorporated into projected sea-level rise estimates, which thus may be underestimated.

Over half of human carbon dioxide emissions to the atmosphere are absorbed by the ocean and land biospheres (Sarmiento and Gruber, 2002), and the excess carbon absorbed by the ocean results in increased ocean acidity. The physical and chemical mechanisms by which this occurs are well understood. Once carbon dioxide enters the ocean, it combines with water to form carbonic acid and a series of acid-base products, resulting in a lowering of pH values. The amount and distribution of human-generated carbon in the oceans are well determined from an international ocean survey conducted in the late 1980s and early 1990s (Sabine *et al.,* 2004). The rate of ocean carbon uptake is controlled by ocean circulation. Most of the excess carbon is found in the upper few hundred meters of the ocean (upper 1,200 feet) and in high-latitude regions, where cold dense waters sink into the deep ocean. Surface water pH values have already dropped by about 0.1 pH units from preindustrial levels and are expected to drop by an additional 0.14–0.35 units by the end of the 21st century (Orr *et al.,* 2005).

Climate Change and Ocean Acidification Impacts on Marine Ecosystems

Climate change and ocean acidification will exacerbate other human influences on fisheries and marine ecosystems such as over-fishing, habitat destruction, pollution, excess nutrients, and invasive species. Thermal effects arise both directly, via effects of elevated temperature and lower pH on individual organisms, and indirectly via changes to the ecosystems on which they depend for food and habitat. Acidification harms shell-forming plants and animals including surface and deep-water corals, many plankton, pteropods (marine snails), mollusks (clams, oysters), and lobsters (Orr *et al.,* 2005). Many of these organisms provide critical habitat and/or food sources for other organisms. Emerging evidence suggests that larval and juvenile fish may also be susceptible to pH changes. Marine life has survived large climate and acidification variations in the past, but the projected rates of climate change and ocean acidification over the next century are much faster than experienced by the planet in the past except for rare, catastrophic events in the geological record.

One concern is that climate change will alter the rates and patterns of ocean productivity. Small, photosynthetic phytoplankton grow in the well-illuminated upper ocean, forming the base of the marine food web, supporting the fish stocks we harvest, and underlying the biogeochemical cycling of carbon and many other key elements in the sea. Phytoplankton growth depends upon temperature and the availability of light and nutrients, including nitrogen, phosphorus, silicon and iron. Most of the nutrient supply to the surface ocean comes from the mixing and upwelling of cold, nutrient rich water from below. An exception is iron, which has an important additional source from mineral dust swept off the desert regions of the continents and transported off-shore from coastal ocean sediments. The geographic distribution of phytoplankton and biological productivity is determined largely by ocean circulation and upwelling, with the highest levels found along the Equator, in temperate and polar latitudes and along the western boundaries of continents.

Key climate-plankton linkages arise through changes in nutrient supply and ocean mixed layer depths, which affect the light availability to surface phytoplankton. In the tropics and mid-latitudes, there is limited vertical mixing because the water column is stabilized by thermal stratification; *i.e.,* light, warm waters overlie dense, cold waters. In these areas, surface nutrients are typically low, which directly limits phytoplankton growth. Climate warming will likely further inhibit mixing, reducing the upward nutrient supply and thus lowering biological productivity. The nutrient-driven productivity declines even with warmer temperatures, which promote faster growth. At higher latitudes, phytoplankton often have access to abundant nutrients but are limited by a lack of sunlight. In these areas, warming and reduced mixed layer depths can increase productivity.

A synthesis of climate-change simulations shows broad patterns with declining low-latitude productivity, somewhat elevated high-latitude productivity, and poleward migration of marine ecosystem boundaries as the oceans warm; simulated global productivity increased by up to 8.0 percent (Sarmiento *et al.,* 2004). While not definitive proof of future trends, similar relationships of ocean stratification and productivity have been observed in year to year variability of satellite ocean color data, a proxy for surface phytoplankton (Beherenfeld *et al.,* 2006); satellite data for 1997–2005 from GeoEYE and NASA's Sea-Viewing Wide Field-of-View Sensor (SeaWiFS) show that phytoplankton declined in the tropics and subtropics during warm phases of the El Niño-Southern Oscillation (ENSO) marked by higher sea surface temperatures and ocean stratification. Ecosystem dynamics are complex and non-linear, however, and new and unexpected phenomena may arise as the planet enters a new warmer and unexplored climate state. Ocean nitrogen fixation, for example, is concentrated in warm, nutrient poor surface waters, and it may increase under future more stratified conditions, enhancing overall productivity.

Changes in total biological productivity are only part of the story, as most human fisheries exploit particular marine species, not overall productivity. The distributions and population sizes of individual species are more sensitive to warming and altered ocean circulation than total productivity. Temperature effects arise through altered organism physiology and ecological changes in food supplies and predators. Warming and shifts in seasonal temperature patterns will disrupt predator-prey interactions; this is especially important for survival of juvenile fish, which often hatch at a particular time of year and depend up on immediate, abundant source of prey. Temperature changes will also alter the spread of diseases and parasites in both natural ecosystems and marine aquaculture. Warming impacts will interact and perhaps exacerbate other problems including over-fishing and habitat destruction.

Food-web interactions are often complicated, and we should expect that some species will suffer under climate change while others will benefit. Broadly speaking though, warm-water species are expected to shift poleward, which already appears to be occurring in some fisheries (Brander, 2006). Biological transitions, however, may be abrupt rather than smooth. Large-scale regime shifts have been observed in response to past natural variability. Regime shifts involve wholesale reorganizations of biological food-webs and can have large consequences from plankton to fish, marine mammals and sea-birds. Thus, rather subtle climate changes or ocean acidification may have the potential to disrupt commercially important species for either fisheries or tourism. Decadal time-scale regime shifts have been documented in the North Pacific, and in the Southern Ocean observations show a large-scale replacement of krill, a food source for mammals and penguin, by gelatinous zooplankton called salps.

A number of other factors also need to be considered. Species that spend part of their life-cycle in coastal waters will be impacted by degradation of near-shore nursery environments, such as mangrove forests, marshes and estuaries, because of sea-level rise, pollution and habitat destruction. Rainfall and river flow perturbations will alter coastal freshwater currents, affecting the transport of eggs and larvae. Some of the largest fisheries around the world, for example off Peru and west coast of Africa, occur because of wind-driven coastal upwelling, which may be sensitive to climate change. Warming will reduce gas solubility and thus increases the likelihood of low oxygen or anoxia events already seen in some estuaries and coastal regions, such as off the Mississippi River in the Gulf of Mexico.

Knowledge Gaps and Ocean Research Priorities

Accurate projections of climate change and ocean acidification impacts on living marine resources hinge on several key questions: (1) how will greenhouse gas and aerosol emissions and atmospheric composition evolve in the future? (2) how sensitive are regional-scale ocean physics and chemistry to these changes in atmospheric composition? and (3) how will individual species and whole-ocean ecosystems respond? Fossil fuels are deeply intertwined in the modern global economy, and carbon dioxide emissions depend upon changing social and economic factors that are not well known: global population, per capita energy use, technological development, national and international policy decisions, and deliberate climate mitigation efforts. Future projections of atmospheric carbon dioxide levels are also relatively sensitive to assumptions about the behavior of land and ocean carbon sinks, which are expected to change due to saturation effects and responses to the modified physical climate (Fung *et al.,* 2005). Climate change on local and regional scales is more relevant for people and ecosystems than global trends. While progress is being made, improved and better-validated regional ocean climate forecasts remain a major need for future research.

Even when predictions about the physical environment are well known, significant knowledge gaps exist about ocean ecology, hindering the creation of the skillful forecasts needed to guide ocean management decisions. While not precluding taking action now to address climate change and ocean acidification, better scientific understanding will help refine ocean management in the long-term. Several elements need to be pursued in parallel: improved on-going monitoring of ocean climate and biological trends; laboratory and field process studies to quantify biological climate sensitivities; historical and paleoclimate studies of past climate events; and incorporation of the resulting scientific insights into an improved hierarchy of numerical ocean models from species to ecosystems.

Rapid advances in *in situ* sensors and autonomous platforms, such as moorings, floats and gliders, are revolutionizing ocean measurements, and ocean observing networks are being constructed for coastal and open ocean regions (*e.g.,* Gulf of Maine Ocean Observing System *http://www.gomoos.org/;* Pacific Coast Ocean Observing System *http://www.pacoos.org/;* National Science Foundation Ocean Observing Initiative *http://www.ooi.org*). The number of historical, multi-decadal ocean time series is limited, but their scientific utility is almost unrivalled. Federal commitment is needed for continued, long-term investment in ocean monitoring and enhanced coordination across observing networks.

In a similar vein, satellite measurements provide an unprecedented view of the temporal variations in ocean climate and 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 climate-change trends is challenging, and 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 plankton, 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 fully preclude new ocean satellite missions needed to characterize ocean climate and biological dynamics.

We need to know if there are climatic tipping points or thresholds beyond which climate change may induce rapid and dramatic regime shifts in ocean ecosystems. Many current scientific studies examine climate sensitivities of species in isolation; the next step involves examining responses of species populations, communities of multiple interacting species, and entire ecosystems to realistic size perturbations. Experiments on plankton and benthic communities can be conducted under relatively controlled conditions in mesocosms (large enclosed volumes such as aquarium or floating bags deployed at sea) or by deliberate open-water perturbations studies. Both approaches will benefit from further directed technological developments. Larger mobile species require different approaches such as using past climate events as analogues for human-driven climate change. Biology models are pivotal to ocean management. They are being improved progressively by incorporating new information from laboratory and field experiments and by comparing model forecasts with real-world data. It is often as important to identify where the models do poorly as where they do well because research can then be focused on resolving these model errors.

Climate Adaptation, Mitigation, and Ocean Management

Given the potential for significant negative impacts of climate change and ocean acidification on living marine resources, we need to develop comprehensive local, national and international ocean management strategies that fully incorporate climate change and acidification trends and uncertainties. The strategies should follow a precautionary approach that accounts for the fact that ocean biological thresholds are unknown. The strategies should include improved scientific information for decision-support, adaptation to reduce negative climate change and acidification impacts, and mitigation to decrease the magnitude of future climate change and acidification.

Currently the United States and other countries invest significant resources in monitoring the ocean and improving scientific understanding on many of the physical, chemical and biological processes relevant to climate change and acidification. However, this wealth of data and information is typically not in a form that is easily accessible by ocean resource managers and other stakeholders, ranging from private citizens and small-businesses to large corporations, NGO's and national governments. For example, even state-of-the-art climate projections typically resolve climate patterns at relatively coarse spatial resolutions and include either relatively simple ocean biology or no ocean biology at all. In contrast, decisionmakers need information tailored to specific local fisheries and ecosystems. The national climate modeling centers should be encouraged to create on a routine basis targeted ocean biological-physical forecasts on seasonal to decadal time-scales, building on nested regional models, probabilistic and ensemble modeling of uncertainties, and downscaling methods developed for related applications (*e.g.,* agriculture, water-resources). The utility of such forecasts and their uncertainties will be maximized if stakeholders are involved in their design from the onset and if the model results are translated into more accessible electronic forms that are widely distributed to the public.

A second challenge is to create more adaptive ocean management strategies that emphasize complete and transparent discussion on the risks and uncertainties from climate change and ocean acidification. Some amount of climate change and acidification is unavoidable because of past greenhouse emissions, and even under relatively optimistic scenarios for the future, substantial further ocean impacts should be expected at least through mid-century and beyond. Decisions will need to be made in the face of uncertainty, relying on for example the precautionary principle to limit future risk. Climate change trends are growing in magnitude, but will still be gradual compared with natural interannual variability; management policies must include both types of variations and uncertainties. Empirical approaches developed from historical data cannot be used in isolation because climate change will shift the baseline for ocean biological systems. Serious efforts should be directed at reducing other human factors such as overfishing and habitat destruction to allow more time for ecosystems and social systems to adapt. Mechanisms such as marine reserves, that protect specified geographical locations, need to account for the fact that ecosystem boundaries will shift under climate change. Procedures also need to be in place to monitor over time the effectiveness of ocean conservation and management policies, and that information and improved future climate forecasts should be used to modify and adapt management approaches.

The third challenge is to pursue climate mitigation approaches that limit the emissions of carbon dioxide and other greenhouse gases to the atmosphere or that remove fossil-fuel carbon dioxide that is already in the atmosphere. Stabilizing future atmospheric carbon dioxide at moderate levels to minimize climate change impacts will require a mix of approaches, and no single mechanism will solve the entire problem. Emissions of carbon dioxide can be reduced through energy conservation and transition to alternative, non-fossil fuel based energy sources (wind, solar, nuclear, biofuels). Attention also needs to be placed in the near-term on limiting other greenhouse gases such as chlorofluorocarbons, which may provide additional time to tackle the more challenging issues associated with carbon. Progress is being made on approaches that would remove carbon dioxide at power plants so that it can be sequestered in subsurface geological reservoirs (*e.g.,* old oil and gas fields, salt domes).

Mitigation approaches have also been proposed using ocean biology, but these methods should only be pursued if critical questions are resolved on their effectiveness and environmental consequences. Biological mitigation strategies are based on the fact that plants and some marine microbes naturally convert carbon dioxide into organic matter during photosynthesis. Enhancing biological carbon removal can reduce atmospheric carbon dioxide if the additional organic matter is stored away from the atmosphere for multiple decades to a century or longer. The deep-ocean is one such reservoir because it exchanges only slowly with the surface and atmosphere. Thus one potential mitigation method would be to fertilize the surface ocean phytoplankton so that they produce and export more organic carbon into the deep ocean. In many areas of the ocean, phytoplankton growth is limited by the trace element iron, which is very low in surface waters away from continents and dust sources. About a dozen scientific experiments have been conducted successfully showing that adding iron to the surface ocean causes a phytoplankton bloom and temporary drawdown in surface water carbon dioxide. But there remain outstanding scientific questions about whether iron resulted in any enhanced long-term carbon storage in the ocean.

As with any other mitigation approach on land or in the sea, the scientific and policy communities need to work closely to assure that the following questions are answered for large-scale commercial ocean fertilization. Is the method effective in removing carbon from the atmosphere, can the removal be validated, and how long will it remain sequestered? Could the method result in unintended consequences such as enhanced emissions of other, more powerful greenhouse gases (in the case of iron fertilization potentially nitrous oxide and perhaps methane)? What are the broad ecological consequences, and could carbon mitigation efforts conflict with maintaining living marine resources and fisheries? Systematic approaches to verify effectiveness and environmental impacts need to be put in place to assure a level playing field for commercial mitigation and carbon credit trading systems.

Conclusions

Over the past two centuries, human activities have resulted in the buildup in the atmosphere of excess carbon dioxide, other greenhouse gases and aerosols. There is now significant evidence that these changes in atmospheric composition are altering the planet's climate. Human-driven climate change is expected to accelerate over the next several decades, leading to extensive global warming, sea-ice retreat, sea-level rise, ocean acidification, and alterations in the freshwater cycle. As the reality of climate change is becoming clearer, the emphasis shifts toward understanding the impact of these climate perturbations on society and on natural and managed ecosystems.

Marine fisheries and ocean ecosystems are susceptible to global warming and ocean acidification. While ocean biological responses will vary from region to region, some broad trends can be identified including poleward shifts in warm-water species and reduced formation of calcium carbonate by corals and other shell-forming plants and animals. For fisheries, climate change impacts will interact and perhaps exacerbate other problems including over-fishing and habitat destruction. Management strategies are needed balancing adaptation to an evolving climate and mitigation to reduce the magnitude of future climate change and atmospheric carbon dioxide growth. Decision support tools should be developed for marine resource managers that incorporate the emerging scientific understanding on climate change, focusing on impacts over the next several decades. Systematic testing is required on the effectiveness and environmental consequences of climate mitigation approaches, such as deliberate iron fertilization, designed to sequester additional carbon in the ocean.

Thank you for giving me this opportunity to address this Subcommittee, and I look forward to answering your questions.

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Senator CANTWELL. Thank you very much.

Dr. Feely, thank you very much for being here. We are very proud, obviously, of the Pacific Marine Environmental Laboratory in the Northwest and we appreciate you being here as NOAA's representative today.

STATEMENT OF RICHARD A. FEELY, PH.D., SUPERVISORY CHEMICAL OCEANOGRAPHER, PACIFIC MARINE ENVIRONMENTAL LABORATORY, NOAA, U.S. DEPARTMENT OF COMMERCE

Dr. FEELY. Thank you very much. Good morning, Madam Chair Cantwell, Ranking Member Stevens, and members of the Subcommittee. My name is Richard Feely and I am a Supervisory

Oceanographer at NOAA's Pacific Marine Environmental Laboratory in Seattle. Part of NOAA's mission is to understand and predict changes in Earth's environment. My area of expertise and the focus of my research is that of the study of the ocean's carbon cycle and its effect on marine life. Thank you for inviting me today to provide my insights on ocean acidification and its effects on living marine resources.

Over the past 200 years the release of carbon dioxide from our collective industrial and agricultural activities has resulted in atmospheric CO_2 concentration increases of about 100 parts per million. During this period the oceans have absorbed 525 billion tons of carbon dioxide from the atmosphere. This is about one-third of human-generated carbon dioxide emissions. The oceans' daily uptake of 22 million tons of carbon dioxide is now starting to have a significant impact on the chemistry and biology of the oceans.

Hydrographic surveys and modeling studies reveal the chemical changes that have taken place. We see change in the lowering of the pH. This pH is a measure of the acidity and the acidity of our oceans has changed by 30 percent since the beginning of the Industrial Revolution. Our projections through the end of the century suggest that the acidity may change by as much as 150 percent if we follow CO_2 emissions scenarios based on the IPCC IS92a projections.

This process of acidification of the oceans is causing a lowering of the carbonate ion concentration levels as well. The carbonate ion plays an important role in shell formation for a number of marine organisms, such as corals, marine plankton, and shellfish. Many marine organisms which use carbonate ions to produce calcium carbonate shells experience detrimental effects due to these increasing CO_2 levels.

For example, ocean acidification is shown to significantly affect coral reefs. It reduces the ability of rebuilding corals to produce their skeletons, affecting growth of individual corals and making the reefs more vulnerable to erosion. 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 affect the thousands of species that depend on this particular habitat.

In long-term experiments, corals grown under the most acidic conditions for periods more than 1 year have not shown the ability to adapt their calcification rates to these higher CO_2 levels. In fact, a recent study has shown that projected CO_2 increase in the oceans is sufficient to dissolve the calcium carbonate skeletons of some coral reef species.

Ongoing research has shown that the increase in acidity may have deleterious impacts on commercially important fish and shellfish larvae. Both king crab and silver seabream larvae exhibit a very high mortality rate in CO_2-rich waters. The calcification rates of the edible mussel and Pacific oyster of the Pacific Northwest region decline linearly with increasing CO_2 levels. Squid are especially sensitive to ocean acidification because it directly affects their blood oxygen transport and respiration. Scientists have been seeing a reduced ability of marine algae, free-floating plants and animals to produce their protective calcium carbonate shells.

One of these free-swimming mollusks is called a pteropod. Pteropods are eaten by organisms ranging from krill to whales and are a major food source for North Pacific juvenile salmon and serve as food for mackerel, pollock, herring, and cod. Ocean acidification is one of the most significant and far-reaching consequences of the buildup of human-generated carbon dioxide in the atmosphere and the oceans. Results from laboratory, field, and modeling studies, as well as evidence from the geological record, clearly indicate that many ecosystems are highly susceptible to changes in ocean CO_2 and the corresponding decrease in pH and increase in acidity. Because of the very clear potential for ocean-wide effects of ocean acidification at all levels of the marine ecosystem from the tiniest phytoplankton to the zooplankton to fish and shellfish, we can expect to see significant effects that are immensely important for mankind.

Ocean acidification is an emerging scientific issue and much research is needed before all the species and ecosystem 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. Ocean acidification demands serious and immediate attention.

For these reasons, the national and technological scientific communities have recommended a coordinated research program with four major themes: carbon system monitoring, calcification and physiological response studies under both laboratory and field conditions, environmental and ecosystem modeling studies, and socioeconomic risk assessments. This research will provide resource managers with the basic information they need to develop strategies for protection of species, habitats, and ecosystems.

I am deeply grateful for the opportunity to discuss this issue with you and look forward to answering your questions.

[The prepared statement of Dr. Feely follows:]

PREPARED STATEMENT OF RICHARD A. FEELY, PH.D., SUPERVISORY CHEMICAL OCEANOGRAPHER, PACIFIC MARINE ENVIRONMENTAL LABORATORY, NOAA, U.S. DEPARTMENT OF COMMERCE

Introduction

Good morning, Chairman Cantwell and members of the Subcommittee. Thank you for giving me the opportunity to speak with you today on the short- and long-term impacts of ocean acidification on marine resources. My name is Richard Feely, I am a Supervisory Chemical Oceanographer 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 its impact on marine organisms. I have worked for NOAA for more than 32 years and have published more than 160 peer-reviewed scientific journal articles, book chapters and technical reports. I serve on the U.S. Carbon Cycle Science Program Scientific Steering Group and I am the co-chair of the U.S. Repeat Hydrography Program Scientific Oversight Committee. For today, you have asked me to provide my insights on ocean acidification and its effect on living marine ecosystems. Most of my comments below are derived from the Royal Society Report, *"Ocean Acidification Due to Increasing Atmospheric Carbon Dioxide"* (Raven *et al.,* 2005) and the recent U.S. report, derived from a workshop held jointly by the National Science Foundation (NSF), NOAA, and the U.S. Geological Survey, entitled *"Impacts of Ocean Acidification on Coral Reefs and Other Marine Calcifiers "* (Kleypas *et al.,* 2006).

Ocean Acidification

Over the past 200 years the release of carbon dioxide (CO_2) from our collective industrial and agricultural activities has resulted in atmospheric CO_2 concentrations that have increased by about 100 parts per million (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. The oceans have absorbed approximately 525 billion tons of carbon dioxide from the atmosphere, or about one-third of the anthropogenic carbon 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 minimizing some of the impacts of global warming. However, the ocean's daily uptake of 22 million tons of carbon dioxide is starting to have a significant impact on the chemistry and biology of the oceans. For more than 25 years, NOAA and NSF have co-sponsored repeat hydrographic and chemical surveys of the world oceans, documenting the ocean's response to increasing amounts of carbon dioxide being emitted to the atmosphere by human activities. These surveys have confirmed that the oceans are absorbing increasing amounts of carbon dioxide. Both the hydrographic surveys and modeling studies reveal that the chemical changes in seawater resulting from the absorption of carbon dioxide are lowering seawater pH (Feely *et al.,* 2004; Orr *et al.,* 2005; Caldeira and Wickett, 2005; Feely *et al.,* in press). It is now well established that the pH of our ocean surface waters has already fallen by about 0.1 units from an average of about 8.21 to 8.10 since the beginning of the Industrial Revolution (on the logarithmic pH scale, 7.0 is neutral (*e.g.,* water), with points higher on the scale being "basic" and points lower being "acidic."). Estimates of future atmospheric and oceanic carbon dioxide concentrations, based on the Intergovernmental Panel on Climate Change (IPCC) CO_2 emission scenarios and general circulation models, indicate that by the middle of this century atmospheric carbon dioxide levels could reach more than 500 parts per million (ppm), and near the end of the century they could be over 800 ppm. This would result in a surface water pH decrease of approximately 0.4 pH units as the ocean becomes more acidic, and the carbonate ion concentration would decrease almost 50 percent by the end of the century (Orr *et al.,* 2005). To put this in historical perspective, this surface ocean pH decrease would result in a pH that is lower than it has been for more than 20 million years (Feely *et al.,* 2004). When CO_2 reacts with seawater, fundamental chemical changes occur that cause a reduction in seawater pH. 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 fisheries resource management communities.

Effects of Ocean Acidification on Coral Reefs

Many marine organisms that produce calcium carbonate shells studied thus far have shown detrimental effects due to increasing carbon dioxide levels in seawater and the resulting 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). 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 toward organisms that are not dependent on calcium carbonate. Carbonate structures are likely to be weaker and more susceptible to dissolution and erosion. In long-term experiments corals that have been grown under lower pH conditions for periods longer than 1 year have not shown any ability to adapt their calcification rates to the low pH levels. In fact, a recent study showed that the projected increase in CO_2 is sufficient to dissolve the calcium carbonate skeletons of some coral species (Fine and Tchernov, 2007).

Effects of Ocean Acidification 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 (Litzow *et al.,* submitted; Ishimatsu *et al.,* 2004). Some of the experiments indicated that other physiological stresses were also apparent. Exposure of fish 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.,* in press). 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). 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). 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 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).

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 the existing data and from the geologic record that some coral and shellfish species will be reduced 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). Over the next century, if CO_2 emissions are allowed to increase as predicted by the IPCC CO_2 emissions scenarios, mankind may be responsible for increasing oceanic CO_2 and making the oceans more corrosive to calcifying organisms than anytime since the last major extinction, over 65 million years ago. Thus, the decisions we make about our use of fossil-fuels for energy over the next several decades will probably have a profound influence on makeup of future marine ecosystems for centuries to millennia.

Economic Impacts

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 $60 billion per year. Coastal and marine commercial fishing generates upwards of $30 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*). Nearly half of the U.S. fishery is derived from the coastal waters surrounding Alaska. 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 Alaskan Aleutian Island region. Many commercially important fish species in this region depend on this particular habitat for their survival.

Healthy coral reefs are the foundation of many viable fisheries, as well as the source of jobs and businesses related to tourism and recreation. In the Florida Keys, coral reefs attract more than $1.2 billion in tourism annually. In Hawaii, reef-related tourism and fishing generate $360 million per year, and their overall worth has been estimated at close to $10 billion. In addition, coral reefs provide vital protection to coastal areas that are vulnerable to storm surges and tsunamis.

Conclusions

Ocean acidification may be one of the most significant and far-reaching consequences of the buildup of anthropogenic carbon dioxide in the atmosphere. 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. Corals and other calcifying organisms will be increasingly affected by a decreased capability to produce their shells and skeletons. Other species of fish and shellfish will also be negatively impacted in their physiological responses due to a decrease in pH levels of their cellular fluids. 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 mankind. Ocean acidification is an emerging scientific issue and much research is needed before all of the 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 also quite high, hence demanding serious and immediate attention. For these reasons, the national and international scientific communities have recommended a coordinated scientific research program with four major themes; (1) carbon system monitoring; (2) calcification and physiological response studies under laboratory and field conditions; (3) environmental and ecosystem modeling studies; and (4) socioeconomic risk assessments. This research will provide resource managers with the basic information they need to develop strategies for protection of critical species, habitats and ecosystems, similar to what has already been developed for coral reef managers with the publication of the *Reef Manager's Guide* by the U.S. Coral Reef Task Force to help local and regional reef managers reduce the impacts of coral bleaching to coral reef ecosystems.

Thank you for giving me this opportunity to address this Subcommittee. I look forward to answering your questions.

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Senator CANTWELL. Thank you very much.

Dr. Conover?

STATEMENT OF DAVID O. CONOVER, PH.D., DEAN AND DIRECTOR, MARINE SCIENCE RESEARCH CENTER, STONY BROOK UNIVERSITY

Dr. CONOVER. Good morning, Chair Cantwell, Ranking Member Stevens, and members of the Subcommittee. My name is David Conover. I am a fisheries scientist and I also serve as Dean of Marine and Atmospheric Sciences at Stony Brook University on Long Island, New York. I am mostly going to talk about the effect of ocean warming on fisheries.

I have studied the ecology of marine fishes along the U.S. East Coast for over 30 years. My message is this. We already see strong evidence of the effects of ocean warming on fish and shellfish along the East Coast. The evidence includes declines in cold-water species due to heat stress and disease, northward expansion of southern species, and explosions of invasive species. Let me explain what is going on.

Because most animals in the sea are cold-blooded, ocean temperature has an enormous direct impact on their biology. We know a lot about the direct thermal effects at the species level, less so at the ecosystem level. But we know enough to make strong predictions.

All species are adapted for life over a relatively narrow range of temperatures. Some species like it warm, others like it cold. Certain regions of the world ocean, particularly the East Coast, have transition zones between cold-water and warm-water habitats. That is where you are going to first see the impacts of warming. My home state of New York sits right in the middle of a transition zone. We are the southern end point for northern species like cod, herring, and American lobsters and we are at the northern end point for southern species like weakfish, fluke, and bluefish.

Here is what we see happening in New York. In 1999, we had a massive summer die-off of lobsters in Long Island Sound, followed by continued summer mortality in subsequent years. The probability is that lobsters cannot tolerate the exceptionally warm summer temperatures we have been having. Heat stress leads to physiological, pathogenic, and parasitic diseases. The result has been an 85 percent reduction in landings, and these diseases now appear to be moving northward.

Another example is a parasitic disease called dermo. It causes catastrophic mortality of oysters. Prior to 1990, this parasite was unknown north of Chesapeake Bay. In the 1990s dermo underwent a massive northward range expansion, extending all the way into the Gulf of Maine. The expansion occurred during years when winters were unusually warm. Dermo is now highly prevalent from Delaware Bay to Cape Cod, with no signs of abating.

Winter flounder is another species at the southern end of its range in New York. It too is declining drastically in our area. Commercial landings in New York are only 15 percent of what they were a few years ago. And it is not just winter flounder. When you look at the fin fish community of Long Island Sound as a whole over the last 15 years, nearly all of the cold-water species have been declining and nearly all of the warm-water species are increasing.

Finally, there is the problem of invasive species. The recent trend of warmer winters in Long Island Sound has favored the growth and recruitment of exotic species over natives. Invasive sea squirts that like winters that are warm are coating the bottom of Long Island Sound, driving away native species.

What do we do about this? From a fishery management perspective, we need to recognize that harvested populations near the limits of their ranges will need extra precautionary measures to protect them from extinction. Predators, pathogens, parasites and invasive species are moving across ecosystem boundaries. We may need to reduce harvest of some of these species in certain areas to enable them to withstand additional stress.

Of course, the ultimate and best solution is the reduction of greenhouse gases. One way of doing this, advocated by some scientists and soon to be commercialized, is the purposeful fertilization of the open ocean with iron. The idea is that phytoplankton blooms will draw carbon out of the atmosphere. Here we need to be careful. Fertilizing aquatic systems almost always has some undesirable consequences. Hypoxia in Long Island Sound, for example, results largely from over fertilization by nitrogen. Sometimes enrichment causes blooms of harmful algal species like red tide or brown tide. The pros and cons of iron fertilization need much further investigation.

Regarding ocean acidification, my colleagues have already discussed this issue. I just want to underscore that there will be direct impacts of acidification on marine fishes. It is a problem we need to look more seriously at.

Also, changes in habitat due to loss of coral and shellbed habitats will alter the food web that supports our fisheries. We need to understand these complex interactions.

Finally, I want to underscore the need for a comprehensive ocean observation system. Scientists are frequently asked to explain catastrophes like the die-off of lobsters in Long Island Sound. We need an observation system that can track environmental changes before, during, and after these events to provide the clues to what happened. Otherwise we are like the detective at the scene of a crime, with no evidence and lots of potential suspects.

The technology exists. Let us put it to use. Such observation systems will greatly aid resource managers in ensuring sustainable fisheries. Thank you and I look forward to answering your questions.

[The prepared statement of Dr. Conover follows:]

PREPARED STATEMENT OF DAVID O. CONOVER, PH.D., DEAN AND DIRECTOR, MARINE SCIENCES RESEARCH CENTER, STONY BROOK UNIVERSITY

Introduction

I thank Madame Chair Cantwell, Ranking Member Snowe, and the other Members of the Subcommittee for the opportunity to describe to you the likely consequences of climate change on marine fisheries. My name is David Conover. I am the Dean and Director of the Marine Sciences Research Center of Stony Brook University, Long Island, New York. My research expertise involves the ecology and natural history of marine fishes and the impacts of harvesting and other human influences on wild fish populations. Of particular relevance to the subject of this hearing, I have devoted much of my 30-year career to studying the physiological mechanisms by which fish adapt evolutionarily to climate change. Much of this work concerns species that live along the East Coast of North America from Florida to the Canadian maritimes, a region that encompasses dramatic changes in climate. We can learn a lot about what to expect from climate change by studying species that span the U.S. East Coast.

You have asked me to address the consequences of climate change for fisheries, fish habitats, the distribution and abundance of species, food webs, and the gaps in our knowledge that preclude our ability to predict immediate and long term impacts. In addition, you have asked for suggestions on how resource managers should respond to these threats. I will begin by briefly outlining the major changes in the ocean ecosystems that are already underway and are expected to accelerate in the years ahead, touching briefly on ocean acidification and then devoting most of my attention to the effects of warming. Both the direct and indirect impacts of acidification and warming will be highlighted. I will then discuss several East Coast examples where already there is strong evidence that climate change is harming local species and altering ecosystems in transitional zones. Finally, I'll talk about short-term solutions and research needed to provide a longer-term prognosis and options for the future.

Ocean Acidification

Knowledge of the potentially devastating impact of reduced pH on aquatic ecosystems is not new. Decades ago it became evident that acid rain was afflicting numerous freshwater ecosystems leading to declines and extinctions of numerous fish and macro-invertebrate species from certain lakes and streams that lacked a natural buffering capacity. What is new is the recognition that acidification of entire oceans is possible. It is caused not by acid rain, however, but from increased CO_2 in the atmosphere, which in turn leads to increased carbonic acid in the ocean.

Most of our knowledge of the direct effects of ocean acidification on marine organisms focuses on species known as "marine calcifiers" (*e.g.,* corals, mollusks) that build skeletons or shells made of calcium carbonate. Many of these species will suffer impaired ability to build skeletons as pH decreases. We know less about the direct impacts of acidification on harvested species like fishes and squids. In these species, the response to acidification is likely to involve physiological diseases including acidosis of tissue and body fluids leading to impaired metabolic function. Egg and larval stages are likely to be much more susceptible than adults, suggesting that reduced reproductive success will be among the first symptoms to appear. The indirect effects of acidification on fisheries will include loss of reef habitat constructed by marine calcifiers. Many fishes depend on the physical structure provided by coral skeletons or shell-building organisms such as oyster reefs as essential habitat for one or more life stages. In addition, food web alterations will likely affect harvested species through bottom-up effects on the food chain resulting from pH-induced shifts in the plankton community. More research is needed to understand these complex interactions.

Ocean Warming

Temperature is a pervasive environmental factor with direct effects on nearly all aspects of the ecology, physiology, morphology, and behavior of poikilothermic or so-called "cold-blooded" animals. There is a vast scientific literature describing the temperature-dependence of physiological processes and thermal ecology of individuals of a given species. Less is known about population and ecosystem level responses to temperature change but we know enough to make fairly strong, general predictions about the consequences of warming at least for the species level.

All species are adapted for life over a relatively moderate range of temperatures compared with the extremes experienced form the poles to the tropics. Temperatures below the optimal range slow the rate of metabolism and, if too low, can become lethal. Temperatures above the optimal range increase metabolism and, because warmer water contains less dissolved oxygen, a thermal threshold is reached where respiratory demand exceeds the capacity for oxygen uptake, sometimes referred to as the "temperature-oxygen squeeze" (Portner and Knust 2007). Hence, temperature is one of the primary environmental factors that determine the geographic range of a species. Minimum winter temperatures often determine the high-latitude boundary (the northern boundary in the northern hemisphere) while summer maximums determine the low-latitude limit of a species. Even within the normal range of a species, the dynamics of populations often show strong correlations with temperature trends.

While scientists can use the thermal physiology of a species to predict how it might respond to the direct effects of ocean warming, there are indirect effects at the ecosystem level that complicate the overall impact considerably. In temperate regions, for example, the complex of species found at a given latitude are a mixture of those adapted to colder or warmer thermal regimes. These species are interconnected through a web of predatory, competitive, pathogenic, parasitic, and mutualistic interactions that influence the abundance of species. Invasive species also sometimes get a foothold more easily in systems undergoing disturbance. In addition, changes in temperature may influence the overall primary productivity of ecosystems in either positive or negative directions (Behrenfeld *et al.,* 2006), which may ultimately impact fisheries yields.

In general, the impact of ocean warming should be most evident at the northern and southern boundaries of the distribution of a given species. These boundaries tend to be shared among numerous species, and they tend to occur where there are sharp discontinuities in thermal gradients. Hence, there are certain regions of the world ocean that are transitional zones for numerous species. Cape Hatteras and Cape Cod are two such regions. It is within these transitional regions where we are likely to first see the strongest impacts of climate change. Most of the phenomena described above are illustrated by changes we are now seeing along the East Coast of the U.S., particularly within Long Island Sound.

Impacts of Warming on Fisheries as Exemplified by Long Island Sound

The Long Island region has represented a thermal transition zone for thousands of years. During the Pleistocene, this region was the transition from glaciated to non-glaciated terrain. Today it still represents a subtle but ecologically important transitional zone between warm-water and cold-water regions.

Most temperate marine species of fishes and macro-invertebrates can be described as having either cold-water or warm-water affinities. Northern species like cod, winter flounder, and American lobster are classic cold-water species. For many of these species, the Long Island Sound region represents that southern terminus of their migration and/or geographic distribution. Southern species like weakfish, summer flounder, and blue crab are physiologically adapted to warm temperatures. Long Island Sound represents the northern end of their geographic occurrence. We are seeing strong evidence of shifts in the relative abundance of cold-water and warm-water species in our region that are consistent with the predictions of ocean warming.

The most well studied example is American lobster. Massive, catastrophic summer–fall mortalities of lobsters in Long Island Sound began in August 1999, and have continued to occur to a greater or lesser degree in subsequent summers. An extensive federally-sponsored research program has identified summer warming of Long Island Sound bottom waters, coupled with hypoxia, and the outbreak of disease as the most likely causes. One of these diseases called “excretory calcinosis”, discovered by scientists at Stony Brook University, is a gill tissue blood disorder resulting directly from warm temperatures (Dove *et al.,* 2004). Other lobster diseases also appear to result from the stress of high temperature and hypoxia. The result of these multiple stresses has been a 75 percent reduction in total landings and 85 percent reduction in the overall abundance of the population. These diseases now appear to be moving northward.

Another example of climate-induced effects on fisheries involves the northward expansion of a disease known as “dermo” that afflicts the oyster. It is caused by *Perkinsus marinus,* a parasite that yearly kills 50 percent of oysters in the Gulf of Mexico. Prior to the late 1980s, the parasite was known to occur only south of lower Chesapeake Bay. In the early 1990s, however, dermo underwent a 500 km northward range expansion extending all the way into the Gulf of Maine. Researchers at Rutgers University have demonstrated that the range expansion occurred during years when winters were unusually warm (Ford and Smolowitz 2007). The prevalence of dermo is now high from Delaware Bay to Cape Cod, with no signs of abating.

Shifts in the relative abundance of finfish in Long Island Sound also bear the signature of ocean warming. Like the lobster, winter flounder is also at the southern end of its distribution and it too is showing extremely severe declines. Commercial landings in New York are only 15 percent of what they were 50 years ago. According to annual resource assessment surveys conducted since 1984 by the Connecticut Department of Environmental Protection (CTDEP), winter flounder abundance in Long Island Sound is now less than 10 percent of what it was in 1990. We need more research to determine if winter flounder are declining due to warming temperatures. But when you look at the finfish community of Long Island Sound as a whole (CTDEP 2006), evidence of warming as the causative factor becomes much stronger. Most of the cold-water species of Long Island Sound have been declining over the past 15 years (*e.g.,* lobster, winter flounder, Atlantic herring, cunner, longhorn sculpin, sea raven, ocean pout, winter skate, little skate) while most of the warm-water fishes have been increasing (*e.g.,* striped bass, weakfish, summer flounder, menhaden, scup, striped sea robin, butterfish, Atlantic moonfish, hickory shad).

Finally, there is also evidence from Long Island Sound that the recent trend of warmer winters favors the growth and recruitment of invasive species over those of native species. Researchers from the University of Connecticut showed that exotic ascidian species (sea squirts) benefit more from mild winters while native species benefit more from cold winters (Stachowicz *et al.,* 2002). Overgrowth of bottom habitat by invasive sea squirts is becoming an increasing problem in Long Island Sound.

Implications for Management

Resource managers need to recognize that local populations of species near the limits of their distributional ranges will need additional precautionary measures to protect them from extinction. Warming and acidification represent additional stresses that make populations less resilient to the effects of harvest. We may need to reduce harvest of some species in certain areas to enable them to withstand the additional stress.

Transitional regions are where the impact of climate change will first be evident. These regions are also conduits for species exchange. The transmittal of pathogens, predators, and invasive species across ecosystems will increase as species migrate into new regions across thermal and faunal boundaries such as Cape Cod, which separates the Mid-Atlantic region from the Gulf of Maine. Management practices that transplant species across ecosystems need to be viewed with caution.

Solutions, Their Implications, and Further Research

The ultimate and best solution is the reduction of greenhouse gases that cause acidification and warming. One solution advocated by some scientists and soon to be commercialized is the purposeful fertilization of open ocean habitats that are deficient in iron. The resulting pulses of phytoplankton growth sequester carbon from the atmosphere and may help reduce the buildup of atmospheric CO_2. Although this possibility deserves serious scrutiny, the ecosystem impacts of fertilization in most aquatic ecosystems almost always contain undesirable consequences for water quality, food webs, and fisheries. Hypoxia in Long Island Sound, for example, results largely from over-fertilization by nitrogen, which is the limiting nutrient in many coastal waters. Sometimes the blooms produced by enrichment turn out to be harmful algal species like “red tide” or “brown tide”. The ecological consequences of ocean fertilization on a scale sufficient to stem the build-up of green house gases needs much further research to evaluate the potential risks of unintended negative impacts.

The certainty of climate change and its potential impacts on ocean ecosystems underscore the need for a comprehensive ocean observation system. Our ability to unravel the causes and consequences of ecosystem change is directly dependent on the availability of a continuous time series of many different kinds of environmental data. Gradual trends in highly variable environmental parameters like temperature, oxygen, salinity, pH, chlorophyll, wind, circulation patterns, and others become evident only after many years. Fishery ecologists are frequently asked to explain the cause of episodic events like the die-off of lobsters in Long Island Sound, but we need an observation system that can provide “before, during, and after” data to give us the clues. Otherwise, we are like the detective at the scene of a crime with no evidence and lots of potential suspects. The technology exists to continuously measure numerous physical and biological parameters that will greatly help us understand and therefore devise strategies to cope with ecosystem alterations caused by climate change or other forces. The number and diversity of sensors currently deployed in U.S. ocean waters is woefully inadequate. Such observation systems will greatly aid resource managers in ensuring sustainable fisheries.

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Senator CANTWELL. Thank you, Dr. Conover.

Dr. Hansen?

STATEMENT OF DR. LARA J. HANSEN, CHIEF SCIENTIST, CLIMATE CHANGE PROGRAM, WORLD WILDLIFE FUND

Dr. HANSEN. Thank you very much, Madam Chair.

I'll attempt to make this show up on your screen as well. Perhaps yes, perhaps no. Ah, there we go.

I have submitted written testimony, but for the purposes of my 5 minutes today I would actually like to take people on a more personal journey. In 2001, I was brought to the World Wildlife Fund to help them design conservation strategies to prepare for climate change. Over the course of the past 6 years we have developed this suite of projects and I think that I will take you through a couple of them that really illuminate the challenges that we face in the world's oceans in response to climate change. The basics of that have been presented by the previous speakers very eloquently. I am going to take you through what this means if you are a resource manager or a conservation planner.

In the Florida Keys, which is a place near and dear to my heart—I did my postdoctoral research there—coral bleaching, coral disease, and hurricanes have resulted in the listing of two coral species for the entire range of the Caribbean. It is not clear how we can protect these species from those types of changes since we only see more of it on the horizon.

Currently we are trying to reduce the proximal threats that are not related to climate change in order to increase the resilience of these systems to a changing climate, by reducing things like pollutants. But it is not clear that we can do that for much longer.

In the Bering Sea, we are trying to protect fisheries. The fisheries of the Bering Sea are an enormous industry, not only for the United States but for Russia and many other countries of the world as well. But more importantly, this is a crucial ecosystem to the world's oceans. It is a very productive part of the world and we are trying to see if there are ways we can better manage fisheries to respond to climate change.

We are also working on protecting mangroves around the world because they protect both coral reefs and coastal systems where humans and biodiversity live.

But all of these actions that I talk about, be it better fisheries management, reducing pollution, or restoring habitats, will be inconsequential if climate change is allowed to continue at the rate it currently is. For climate change-increasing temperatures, we recognize that there is about a limit of 2 degrees before we cannot use these types of methods to help these systems.

In the case of ocean acidification, we do not know what that limit is. It is probably fairly low before we start seeing remarkable impacts, because the oceans historically have been believed to have a very high buffering capacity, so we would not need to worry about things like ocean acidification. In fact, that is not the case, as we can all—as Dr. Feely has already indicated.

We are at a point now where we need to not only be dealing with adaptation, but we need to be dealing with mitigation as well. Unfortunately, we are currently dealing with neither. As a result, I suggest a number of things. Obviously, the Congress is doing a great job of taking on issues of mitigation, of reducing greenhouse gas emissions. There are several bills in process for that. But there is virtually nothing in process for what we are doing about adaptation, and we will be seeing the effects of climate change on every sector of society.

We need a national adaption plan or strategy. As part of this, we also need the capacity to deal with climate change. It is almost impossible to find people who know how to design adaptation strategies and adaptation actions, because we have not trained people for these types of activities. We need an adaptation extension agency analogous to the land grant and Sea Grant extension agencies, with also an international component that can help people in other countries adapt.

We have been told, according to the IPCC Second, Third—Fourth Assessment Report, second working group, that it will be the poorest of the poor that will be affected by climate change. In fact, I would argue that we will all be affected by climate change, and I think that the slow recover of the Gulf Coast following Hurricane Katrina is an excellent example of the low adaptive capacity of even the United States, a very wealthy country by world comparison.

We need to act now. We cannot wait and continue to do studies. We are seeing the changes. Obviously we need to continue to learn as we go, but we cannot wait for all the answers before we decide what it is we are going to do. This problem is already upon us.

Thank you very much, Madam Chair.

[The prepared statement of Dr. Hansen follows:]

PREPARED STATEMENT OF DR. LARA J. HANSEN, CHIEF SCIENTIST, CLIMATE CHANGE PROGRAM, WORLD WILDLIFE FUND

"Climate change is arguably the greatest threat to the world's biodiversity." That is how I began my testimony to the Senate Committee on Commerce, Science, and Transportation in March of 2004. Three years later this is no less true. In fact, the situation we find ourselves in is even more dire as was most recently highlighted in the Intergovernmental Panel for Climate Change (IPCC) Fourth Assessment Report released this year. Representing the top scientific experts in their fields, the three working groups of that body present the state of the science as demonstrating that:

1. Climate change is caused by greenhouse gas emissions from fossil fuels, such as carbon dioxide, and land use change;
2. We are already seeing the effects of climate change around us; and
3. We need to take action now both in terms of mitigation and adaptation to avoid an unacceptable future.

The time to act is now.

The primary response among policymakers has been to focus on reducing emissions of greenhouse gases, that is, mitigation of climate change. However, as the IPCC Working Group II emphasized, and as I have emphasized in my work over the years, adaptation—our ability to adjust to and prepare for the changes in climate already occurring and future changes to which our past emissions have already committed us—is now equally important. There is no need to debate the virtues of mitigation versus adaptation. Neither alone will solve our problems. We need both and we need to see meaningful legislation addressing both mitigation and adaptation during this Congressional session.

As part of a conservation organization, my colleagues and I work to protect the world's biodiversity and natural resources. Traditional approaches to this work have relied on creating protected areas, limiting "take" of key species and resources and monitoring ecosystems of great importance and/or at great risk. Climate change makes these approaches inadequate. As the world's oceans warm and acidify, storm intensity increases, sea level rises, timing and concentrations of nutrient and contaminant run-off from terrestrial systems change, currents and upwelling patterns stop or move, timing of migration and lifecycle stages shifts, and ranges of species move, the oceans can not be protected from climate change by these old mechanisms. Conservation is now being planned across a matrix that is changing before our eyes and we are not prepared.

It could further be argued that the United States as a whole is not prepared. The IPCC Fourth Assessment Report asserts that climate change will be hardest on the poorest of the poor globally. The 2005 hurricane season indicates that the United States will not be unscathed by climate change. It is now over a year and a half since a record number of Category 5 storms hit our Gulf Coast, and it has still not recovered from the battering. New Orleans is still in tatters. The calamities of climate change will be events like these and we are not prepared.

To address climate change in our conservation planning, WWF has adopted an approach to increase the resilience of natural systems to climate change that we are employing in ecoregions around the planet. This work is based on four basic tenets:

1. *Protecting adequate and appropriate space.* As the climate changes species (plants and animals) will react to these changes. They will react by altering how they live, such as using new resources, by moving to new areas, or by disappearing because they cannot find the habitat or resources they require. To help ecosystems respond to climate change we need to start planning where protected areas need to be in the future for species survival and how they need to be managed differently to support species groups. We need to look for locations that can act as refuges from climate change, opportunities for networks of reserves along climatological gradients (often across latitude or elevation), locations with high amounts of heterogeneity (or areas with different habitats and species) and opportunities to support genetic diversity and gene flow. All of these strategies try to maximize the opportunity for species or ecosystems to respond to climate change, without adversely affecting ecosystems with our actions.

2. *Reducing all non-climate stresses.* Climate change presents a number of environmental stresses—increasing temperature, altered precipitation patterns, sea level rise, altered environmental chemistry to name just a few—but these stresses are not occurring in a vacuum. There are already a host of other environmental stresses out there, including invasive species, over-harvest, habitat degradation and fragmentation, disease and pests, and pollution. Unfortunately in many cases there are synergistic interactions between these traditional stresses and the stresses of climate change, effectively lowering the effect or "toxicity threshold." To increase ecosystem resilience to climate change we must lower the risk of adverse reactions by lowering the acceptable limits of these other stresses in the environment because climate change is already happening and our actions/inaction has already committed us to some changes.

3. *Implementing these pro-active approaches in adaptive management so we can learn as we go.* The actions we suggest are just good sense in light of climate change. If we enact small-scale tests and wait to implement our approaches broadly, the system will have changed and our approaches may no longer be useful or applicable. The window of opportunity for preparations may close as climate change progresses. Additionally, we do not have the funds or the human capacity to test strategies everywhere so we need to be learning lessons to share and implement as rapidly as possible.

4. *Reduce the rate and extent of climate change.* There is a limit to our ability to adapt to climate change. For example if we think about ocean acidification, there is a permanent commitment to changing the pH of the ocean every time we add more carbon to the atmosphere and it is not at all clear how we can adapt to these changes. Best estimates are that 2° C (3.6° F) increase in average global temperature brings us to a point where adaptation options become dramatically limited in feasibility and efficacy and prohibitively expensive in terms of cost. It is not new thinking that mitigation is necessary. This is simply another reason why we need to act sooner rather than later.

WWF's conservation adaptation projects are being implemented around the world, including in our marine ecoregions. In the tropics, we are testing how to protect coral reefs in American Samoa, Florida and the Mesoamerican Reef of Central America. We are also restoring and protecting mangrove forests to provide better coastal protection in Fiji, Cameroon and Tanzania. We are planning for sea level rise in low lying regions of the world, especially those that are home to endangered species, like endangered sea turtles in the Caribbean and beautiful tigers in the Sundarbans of India. In the Bering Sea of Alaska we are working to protect the future of that region's vital fisheries for the realities of climate change.

Some of our first work on climate adaptation was focused on coral reefs. Coral reefs are particularly sensitive to climate change. They bleach when ocean temperatures climb by as little as one degree Celsius. They are unable to create the calcium carbonate skeleton that forms the reef structure when the pH drops. And, they are damaged by increasingly intense tropical storm activity. The fate of coral reefs will have ramifications for human societies as well. It has been estimated that coral reefs have a global economic value of $30 billon in net benefits. In the case of coral reefs we are particularly interested in increasing resilience by decreasing those non-climate stresses that exacerbate the adverse effects of climate change; those factors that add to the overall stress and prevent corals from being able to withstand the stresses of climate change itself. In American Samoa our research group worked with local stakeholders to assess the current and potential impact of climate change on their coral reef resources. Almost annual coral bleaching in this region may be leading to reef degradation. Increased awareness of this issue in the region, in part due to this project, has lead to climate change being front and center on the agenda of the upcoming U.S. Coral Reef Task Force meeting to be held in American Samoa.

This first project led us to explore similar issues on a reef closer to home. In the Florida Keys, in fact for their whole Caribbean range, there are two species of coral, *Acropora cervicornis* and *A. palmata,* which are listed as threatened under the Endangered Species Act. The top three factors identified as the cause of their listing are increasing sea temperatures, hurricanes and disease. It is unclear how a recovery plan will be developed to respond to these threats given their inextricable link to global climate change and increasing greenhouse gas emissions. However the larger issue in the region is not how to protect these two species but rather how to protect the entire reef ecosystem. We are currently developing a decision-support tool to allow for the integration of historic coral bleaching data and water quality data in order to assess how improving regional water quality in the Keys may increase the resilience of those very economically valuable coral reefs. In 2001 it was estimated that coral reefs generated $3.9 billion in income for Broward, Mimai-Dade, Monroe and Palm Beach counties.

Coral reefs are not the only systems at risk from climate change. Coastal communities, both people and wildlife, also experience multiple climate change challenges—sea level rise, increasing storm intensity, changing precipitation, and increasing temperatures. Couple those stresses with the high human population density and development typical of coastal regions and climate planning becomes quite complicated. In some regions we are working to protect coastline and in other we are preparing for its loss.

Mangrove forests are already one of the most degraded ecosystems in the world. They have been cut down for firewood, building supplies and to clear coastline for development. Unfortunately these trees provide natural protection for shoreline from sea level rise and storm surge. Their loss has increased the vulnerability of coastal communities. WWF is working to restore and protect mangrove forests in order to increase coastal resilience in Fiji, Cameroon and Tanzania. As it turns out there is an added benefit of protecting mangroves; healthy mangroves may support healthy reefs. Mangroves filter nutrients out of the water as it flows from land to the oceans. It turns out coral reefs prefer low nutrient waters and when high nutrient waters flow into the oceans it can decrease the resilience of coral reefs. Additionally mangroves produce a compound that can filter out the harmful ultraviolet radiation that can exacerbate coral bleaching.

Sea level rise means the loss of land. For some species appropriate land is limited; others thrive right along the shoreline. In either of these cases, there are almost always human communities nearby that are also competing for this already precious space. Unfortunately it is getting more precious every day. An interesting case study is the Key Deer, a federally endangered species that finds suitable habitat on just two of the Florida Keys. With an elevation of less than 2 meters (or about six feet) at their highest point the vulnerability of the Florida Keys to climate change is clear. If you are a Key Deer, with nowhere to migrate in response to climate change, your future is grim. While it is not clear what can be done for the Key Deer, WWF is trying to help develop plans to prepare other species for climate change. In the Caribbean basin, we are learning how sea level rise will inundate the nesting beaches of sea turtles. Sea turtles are vulnerable throughout their lives to climate change—their sex is determined by the temperature of the sand in which their eggs incubate, their long migrations and food sources are to varying degrees affected by ocean currents potentially vulnerable to climate, some rely on coral reefs and sea grasses which are themselves vulnerable and then their nesting beaches are being lost as the seas rise. Often as sea level rises, beaches retreat inland creating new coastline that would be suitable for turtle nesting. Unfortunately human infrastructure (buildings, roads) can prevent the generation of suitable new habitat. We are creating a new conservation plan for sea turtles that allows us to assess rate of sea level rise, beach elevations (looking for beaches that can withstand more sea level rise), local geology (subsidence and uplift), and patterns of human development. This will allow for choosing the right places for sea turtle protected areas and developing better coastal planning for not only sea turtles but human populations as well.

On the other side of the planet we are dealing with a similar but potentially more dangerous issue. In the Sundarbans of India, tigers live on low-lying mangrove islands. It is estimated that 12 of these islands will be lost to sea level rise by 2020. These are home to not only the tigers but people as well. As these islands are lost, both tigers and people will be looking for new homes, and with this may come increasing human/wildlife interactions that can have adverse consequences for both sides. We are again trying to develop a new conservation plan to prepare for the habitat that both humans and tigers will need as the landscape changes.

A similar process is occurring in our most northern oceans. In the Arctic, record sea ice loss is causing polar bears to spend more time on land or drown at sea. It is also making them go hungry because they require sea ice to hunt for their primary food source, ringed seals. More time on land means more time for potential interactions with people. In one Russian community where we work a young woman was killed by a polar bear near her village last year. We are now working with these communities on ways to decrease polar bear/human interactions without loss of life on either side through what are called "Polar Bear Patrols."

In the Bering Sea climate change is causing fish species ranges to shift (generally moving farther north) and historic fishing grounds will no longer be as robust. This is no small concern as the Bering Sea is home to a $2.1 billion fishing industry. WWF is working to develop new management approaches that plan for climate change and protect the resource as well as the livelihoods that rely upon it.

Obviously projects like these will not solve the problem of climate change. However they encompass the level of climate awareness that managers must now have and the range of activities they can engage in order to increase the resilience of their systems to climate change. They are part of a larger strategy that we must develop to address both the cause and effects of climate change.

Virtually all of the major bills introduced in this Congress relating to climate change are focused on mitigation, whether in the form of across-the-board cuts in U.S. greenhouse gas emissions, or in more targeted cuts for electric power plants, mobile sources of emissions, etc. Given the crucial need to address the root cause of climate change this is not misguided. However we must now also begin the task of addressing how to respond to the effects of climate change. At this point, bills on climate change have not addressed adaptation in a meaningful way.

Conservation organizations are not alone in their lack of preparedness for the effects of climate change. We need a bold new plan in all sectors to deal with this ubiquitous challenge. WWF proposes a legislative approach with two components. First we need a National Strategy for Adaptation, supported not only with funding, but with an extension agency that works to develop the myriad responses we will need in all sectors of our society, not just the oceans, not just natural resources and wildlife, but in civil society and the infrastructure on which we and our economy relies—food, water, housing, transportation, education, public health . . . the list is endless. This extension agency could be modeled after the Land and Sea Grant programs to work with all levels of society across the country on specifically addressing and adapting to climate change. Second, we need an impact assessment approach modeled after National Environmental Policy Act (NEPA) that would require public works, infrastructure activities and all other projects that might adversely affect natural systems to take into account the added effects of climate change, and address how those adverse effects could be avoided. For instance, some pollutants become more toxic at elevated temperatures, so existing exposure limits may not adequately protect people and ecosystems as the planet warms and this could affect permitting for new sewage treatment projects. In fact this approach of assessing the vulnerability of projects to climate change should be good business practice for all federally funded project in order to ensure their value, success and longevity, regardless of whether they focus on natural resources.

The task of fully addressing climate change is massive, but we can no longer ignore it.

Sustainable Development Law & Policy—Winter 2007

CLIMATE CHANGE AND FEDERAL ENVIRONMENTAL LAW

by Drs. Lara Hansen and Christopher R. Pyke*

Introduction

Human activities, particularly the combustion of fossil fuels and the large-scale transformation of land cover, affect ecosystems around the world, Changes in temperature, precipitation, and water chemistry are altering our environment. These changes will also affect environmental regulatory frameworks, either rendering them ineffective or forcing them to adapt to achieve their goals under changing conditions.

Global temperature has increased by 0.8° C over the last century. Climate scientists estimate that we arc committed to an additional 0.5° C increase due to the amount of carbon dioxide ("CO_2") that is already present in the atmosphere.[1] Rising temperatures have been accompanied by a wide range of environmental changes, including, retreat of sea ice and glaciers, sea level rise, and changes in the intensity and frequency of storms and precipitation events.[2] Rising CO_2 concentrations has not only changed the composition of the air, but it is also changing the chemistry of the water: CO_2 is absorbed by the oceans, which forms carbonic acid, causing the acidification of the oceans.[3]

These changes mean that regulations intended to protect natural resources and promote conservation will be applied under conditions significantly different from those that prevailed when they were drafted. Achieving the original goals of these regulations will require a careful assessment of long-standing assumptions, as well as decisive action to change regulatory practices in ways that accommodate, offset, and mitigate climate change. Three such laws will be explored in this article: the Endangered Species Act ("ESA"), the Clean Water Act ("CWA"), and the Clean Air Act ("CAA").

Climate Change and the Endangered Species Act

The stated purpose of the ESA is "to provide a means whereby the ecosystems upon which endangered species and threatened species depend may be conserved."[4] The architects of the ESA intended to save creatures from proximal threats, such as bulldozers and dams. Yet, today we see clear evidence that climate change creates new threats to already imperiled species by contributing to the disruption of ecological processes essential to entire ecosystems. Deteriorating conditions will impact the viability of endangered species and the practices used to protect them through implementation of the ESA (*e.g.,* listing, "take" permitting, and recovery planning).

For example, in 2006, two species of Caribbean coral, Elkhorn *(Acropora palmata)* and Staghorn *(A. cervicornis)* coral, were listed as "threatened" for their entire range under the ESA. The listing stated that "the major threats to the species' persistence (*i.e.,* disease, elevated sea surface temperature, and hurricanes) are severe, unpredictable, likely to increase in the foreseeable future, and, at current levels of knowledge, unmanageable."[5] This listing identifies three key threats that all relate to climate change: rising sea surface temperatures, disease susceptibility, and hurricane-related impacts. Sea surface temperatures are closely related to increasing global surface air temperatures. A severe Caribbean coral-bleaching event in 2005 demonstrated that high temperatures cause coral bleaching and bleaching corals become more susceptible to disease.[6] Moreover, as global temperatures rise, the intensity and frequency of hurricanes may increase.[7] The timing of this listing was particularly profound as it followed the unprecedented 2005 Caribbean summer, during which the region experienced the hottest water temperatures ever recorded with large-scale bleaching followed by disease,[8] and a record breaking hurricane season.[9]

Recently, the U.S. Fish and Wildlife Service proposed listing Polar Bears *(Ursus maritimus).* The bears rely on Arctic sea ice for access to food and breeding sites. Their primary food source, the ringed seal *(Phoca hispida),* is also an ice dependent species. The loss of nearly 30 percent of Arctic ice cover over the past century, together with the possibility that the Arctic will be seasonally ice-free before the end

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of this century, strongly suggest that climate change will jeopardize the survival of this species.[10]

Another example is the Key Deer, which is now limited to living on two islands in the Florida Keys. Most of the Keys have less than two meters of elevation. If sea levels were to rise one meter, most the Key Deer habitat would be lost. The only way to limit sea level rise and protect remaining Key Deer habitat is to take action to mitigate the rate and extent of climate change.[11]

These three species represent the tip of the iceberg, so to speak. Because climatic conditions are central to basic ecological processes that control the distribution and abundance of life, the list of species that are or will be endangered by climate change is potentially enormous.[12] The most direct way to protect the ecosystems in which these species live—the mandate of the ESA—will be to address the cause of climate change: greenhouse gas emissions. However, because some impacts are inevitable, it is important that we also consider how implementation of the ESA can be used to reduce the vulnerability of imperiled species and aid in their recovery despite changing conditions.

Climate Change and the Clean Water Act[13]

The CWA provides the legislative foundation for the protection and restoration of the waters of the United States. The Act seeks to "restore and maintain the chemical, physical, and biological integrity of the Nation's waters" with the goal of achieving water quality that "provides for the protection and propagation of fish, shellfish, and wildlife, and recreation in and on the water."[14] The CWA gives the U.S. Environmental Protection Agency ("EPA") the statutory authority to establish water quality standards and to regulate the discharge of pollutants into waters of the United States.

Climate and water quality are linked by hydrologic processes involved in the global water cycle. These processes move water from the oceans, into the atmosphere, and back down into rivers, streams, wetlands, and estuaries. The net result is a sustainable supply of clean, fresh water and a wide variety ecosystem services, such as recreational opportunities and food production. It has long been recognized that humans intervene in this cycle through activities that intercept, store, utilize, or otherwise alter natural hydrologic processes (*e.g.,* the expansion of impermeable surfaces, application of excess fertilizer, and removal of ecological filtration processes such as wetlands). The CWA provides a framework for understanding these sources of impairment and acts to restore impaired waters and prevent further degradation. Over time, the CWA contributed to significant improvements in surface water quality in the United States despite a steadily growing population and expanding economy.

Climate change adds a new and potentially disruptive element to these long-running efforts. The Intergovernmental Panel on Climate Change predicts a wide variety of changes, including rising air temperature, more frequent heat waves, more intense precipitation events, and increasingly severe dry-spells and droughts.[15] These changes reflect the biophysical consequences of an overall acceleration of the global hydrologic cycle, and these general conclusions have been a feature of the scientific literature for nearly twenty years. However, the local and regional consequences of these complex processes remain difficult to predict. The key conclusion for local and regional decisionmakers is that "change" will be the operative word, and historic observations will provide an increasingly unreliable guide to future conditions. Changes in hydrologic processes will be reflected in changes in the quantity and quality of surface waters, and, in many cases, they are likely to undermine important assumptions used in the implementation of the CWA. For example:

- More intense precipitation events will increase nonpoint source pollution loads.
- Increasing storm water volumes may exceed expectations and design specifications for water treatment works and sewer infrastructure.
- Decreases in flow volume may increase in-stream pollutant concentrations and reduce the ability of waters to accommodate pollutant discharges.
- Increases in ambient air temperature will raise temperatures in surface waters and threaten aquatic ecosystems.
- Humans may respond to some climate change-related impacts through increased use of some pesticides, fungicides, and fertilizers, increasing the concentrations in surface and groundwater (*e.g.,* expanding nuisance species).
- Climate change may also decrease the toxicity thresholds of bioindicators to these pollutants.

These changes have significant implications for the most important and far-reaching CWA programs, including the control of point source discharge, management of nonpoint source pollution, and environmental monitoring.

Point source discharges are typically managed by engineered systems. Most modern systems are designed to accommodate a relatively wide range of environmental conditions. However, there are limits, and climate change may drive systems unexpectedly close to their design tolerances—sometimes risking catastrophic outcomes (*e.g.,* levies surrounding New Orleans). Changes to long-term, capital-intensive investments such as sewer and stormwater facilities are costly and time consuming. Consequently, those involved in their design, construction, and operation need to begin anticipating the impacts of climate change immediately.

Nonpoint source pollution represents a different kind of problem. By definition, nonpoint loads come from many small sources. Pollution is controlled by means of so-called Best Management Practices ("BMPs"), such as riparian buffers, retention ponds, and cover cropping. Climate change will alter both the volume and concentration of nonpoint source pollution and the effectiveness of BMPs. Managing nonpoint source pollution under changing climatic conditions will require thoughtful monitoring and attention to the relative sensitivities of different land uses and BMPs. In many cases, thoughtful land use planning and the selection of climatically-robust BMPs may be able to achieve many nonpoint source pollution control goals despite changing conditions.

CWA programs are based on observations of the actual water quality conditions and activities that may contribute to impairment. Observations include information about a water body's physical, chemical, and biological condition. These indicators are used to assess compliance with water quality standards and attribute degradation to specific sources. This process typically assumes that drivers of change can be found within a given watershed. However, climate change will alter water quality regardless of local actions and, in most cases, climate-related changes will compound or exacerbate on-going water quality problems and a myriad of existing conditions and on-going restoration activities. In other words, climate change will make an already complicated analysis significantly more challenging.

Untangling complex, changing mixtures of factors contributing to water quality will require monitoring systems that allow for separation of climatic and non-climatic factors. The EPA uses a system of bioindicators to evaluate the biological integrity of surface waters.[16] These are typically fish, aquatic insects, and other organisms that have well-known responses to changes in water quality. These bioindicators provide synthetic measures of water quality that can help diagnose specific causes of impairment or degradation. However, bioindicators are themselves part of ecological systems that will respond to changes in both climate and water quality.[17] The myriad examples offered in toxicological literature demonstrate that elevated temperature and altered water chemistry can exacerbate the toxicity of pollutants. Consequently, the use of this important information for attribution will require understanding the response of specific bioindicators to changing conditions and specifically selecting indicators with methods that allow for partitioning between climatic and non-climatic impacts.[18]

Climate Change and the Clean Air Act

The stated purpose of Title IV of the CAA is "to reduce the adverse effects of acid deposition." [19] It seeks to address Congressional findings that:

1. the presence of acidic compounds and their precursors in the atmosphere and in deposition from the atmosphere represents a threat to natural resources, ecosystems, materials, visibility, and public health;

2. the principal sources of the acidic compounds and their precursors in the atmosphere are emissions of sulfur and nitrogen oxides from the combustion of fossil fuels;

3. the problem of acid deposition is of national and international significance;

4. strategies and technologies for the control of precursors to acid deposition exist now that are economically feasible, and improved methods are expected to become increasingly available over the next decade; and

5. current and future generations of Americans will be adversely affected by delaying measures to remedy the problem.[20]

The CAA is primarily targeted at reduction of sulfur ("SO_X") and nitrogen oxides ("NO_X"). It also may be interpreted or amended to apply to greenhouse gases. Rising atmospheric CO_2-levels acidify ocean water and threaten marine resources and ecosystems. Reducing CO_2 emissions would help mitigate this global problem, potentially using CAA mechanisms originally designed for SO_X and NO_X. For example, Title IV of the CAA encourages "energy conservation, use of renewable and clean alternative technologies, and pollution prevention as a long-range strategy, consistent with the provisions of this title, for reducing air pollution and other adverse impacts of energy production and use."[21] These activities also reduce CO_2, emissions and in so doing mitigate the effect of atmospheric CO_2, on the ocean.

Finally, CO_2, acidification, like SO_X and NO_X, is a problem of national and international scope. Current and future generations will be affected by any delay in taking action. Due to the fact that roughly half of anthropogenic emissions end up in the oceans and because CO_2 remains in the atmosphere for a substantial period of time, CO_2 will continue to acidify the Earth's oceans for decades or centuries to come. Failure to limit anthropogenic emissions will only perpetuate this problem. The likelihood that reducing greenhouse gas emissions will limit acidification is very high.

To date, the EPA has been unwilling to regulate CO_2 as an air pollutant, and legal action by states and municipalities on this issue awaits a decision by the U.S. Supreme Court. Interpreting or amending the CAA to regulate CO_2, as an acidifying agent may be an effective mechanism for curbing CO_2 emissions.

Conclusion

The ESA, the CWA, and the CAA form the foundation of the effort to protect and restore the environment in the United States. Climate change undermines the ambitious goals of these laws. Changes in climate can jeopardize the survival and recovery of endangered species. Climate change is likely to alter hydrologic processes in ways that could undermine the goal of providing clean, safe water resources. Climate change can also exacerbate long-standing air quality issues by increasing the likelihood of unhealthy or ecologically-damaging conditions. The first step is to take our collective foot off our fossil fuel-powered accelerator by implementing prompt and deliberate measures to reduce the emission of greenhouse gases.

This first step, while necessary, is not sufficient. We are already committed to significant levels of climate change due to the accumulation of CO_2, in our oceans and atmosphere. Achieving conservation and resource protection goals will require developing robust and resilient practices that explicitly anticipate and address the potential for changing conditions. In the years ahead, efforts to mitigate and adapt to climate change will constitute important, new dimensions to these critical pieces of environmental legislation.

Endnotes

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[8] NPS, *supra* note 6.

[9] Trenberth & Shea, *supra* note 7.

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[16] U.S. EPA website, Biological Indicators of Watershed Health. *http://www.epa.gov/bioindicators/html/indicator.html* (last visited Feb. 13, 2007).
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[21] 42 U.S.C. § 7651 (2003).

Senator CANTWELL. Thank you, Dr. Hansen.
Dr. Kruse?

STATEMENT OF GORDON H. KRUSE, PH.D., PRESIDENT'S PROFESSOR OF FISHERIES AND OCEANOGRAPHY, SCHOOL OF FISHERIES AND OCEAN SCIENCES, UNIVERSITY OF ALASKA FAIRBANKS

Dr. KRUSE. Madam Chair and members of the Committee: It is my honor to testify to you this morning. My name is Gordon Kruse. I am the President's Professor of Fisheries at the School of Fisheries and Ocean Sciences, University of Alaska, Fairbanks.

My objectives are to discuss potential mechanisms and effects of climate change on living marine resources in Alaska, future outlook for these resources, and implications for management and research needs. As just one measure of the value of marine ecosystems, in 2005 landings from Alaska totaled 5.7 billion pounds, representing 59 percent of the total 9.6 billion pounds landed in the United States.

Because the Arctic has been warming much faster than the rest of the globe and this accelerated trend is projected to persist, studies on its effects in Alaska are critically time sensitive. A large body of scientific evidence implicates climate as being primarily responsible for many observed changes in marine ecosystems off Alaska. Three of the important interrelated scales of variability I will discuss today are inter-annual, decadal, and global warming.

Regarding inter-annual or year to year variability, an important component is the El Niño, which occurs every 2 to 7 years. In association with warm ocean temperatures, species more typical of tropical waters, such as ocean sunfish and Pacific white-sided dolphins, extend their distributions into Alaska. El Niños appear to have become more intense in the latter half of the 20th century, possibly as a manifestation of global warming.

Coincident with the very strong 1997–1998 El Niño, the first ever massive bloom of coccolithophores, which are very small, rather non-nutritious microscopic plants or phytoplankton, was observed in the eastern Bering Sea. The bloom was so massive that it was observed from space. Some seabird species experienced massive die-offs and others produced very few surviving offspring owing to feeding problems.

Much decadal-scale variability occurs in the form of climate regime shifts every 10 to 30 years. For instance, in the northeast Pacific Ocean temperatures were warm in the mid-1920s to the mid-1940s, cool in the mid-1940s to the late 1970s, and warm since then. Marine ecosystem changes since the regime shift of the 1970s include declines in forage fishes, crabs and shrimps, and increases in salmon and groundfish, presumably as a result of changes in nutrients supporting phytoplankton production.

Global warming will have differential thermal effects on the species distributions. In the Bering Sea, adult red king crab and snow crab have shifted to the north since the late 1960s, likely due to an aversion to increasing bottom temperature. It appears that the planktonic larvae of both species are now being carried by ocean currents too far north, beyond preferred nursery habitats. At the same time, warmer temperatures have allowed predators of young crabs, such as Pacific cod and rocksole, to shift their distributions to the north. For these reasons, Bering Sea crabs may fare poorly under continued global warming.

One species that seems to have particularly benefited greatly from conditions since the late 1970s is arrowtooth flounder, a species at its highest record levels of abundance. This species is a voracious predator that consumes large amounts of pollock, cod, and other commercially valuable species. Unfortunately, the flesh of the arrowtooth flounder has low market value owing to enzymes that degrade flesh quality.

The Bering Sea is being restructured by ongoing warming temperatures and loss of sea ice. In years of extensive sea ice, an ice edge phytoplankton bloom occurs in April, which falls to the sea floor and supports bottom or benthic species like crabs and clams. In years of little sea ice, the spring bloom occurs in May or June and it stays in the upper layers, where it benefits water column or pelagic species, like pollock. A sharp decline in sea ice has favored pelagic over benthic species in the southeast Bering Sea since the late 1970s.

Recent studies are indicating that similar changes are now beginning to occur in the northern Bering Sea. In these northern areas, loss of benthic production will adversely affect walruses and spectacled eiders, which feed primarily on benthic clams or other bivalves.

What about implications of global warming on fishery management? The North Pacific Fishery Management Council is considering management actions with respect to likely northward expansion of fish resources into the northern Bering Sea and Arctic Ocean. At its June 2007 meeting, the North Pacific Fishery Management Council is considering action that may ban bottom fishing in the northern Bering Sea except for the conduct of experiments to study fishing effects.

Over the long-term, the Council may develop an Arctic Fishery Management plan, but these efforts are severely constrained by lack of information on marine fish and invertebrate resources in the region.

In general, global warming will cause greater uncertainty about the productivity of fish stocks. Under science-based management, increasing uncertainty translates into more precaution, which will likely mean reduced fish harvests in Alaska.

I have recommended five research needs to improve our ability to forecast and address likely future marine ecosystem changes in Alaska with regard to global warming. First, it is critical at this time to establish baseline assessments of marine ecosystems of the northern Bering Sea and Arctic Ocean.

Second, establishment of Integrated Ocean Observing Systems is essential to monitoring and understanding the effects of global climate change on these marine ecosystems. Third, it is important to invest in studies on the biology, life history, and ecology of very poorly studied species in the northern regions. Fourth, it is important to establish linkages between climate models and marine ecosystem and fishery models, so that the effects of global warming can be better quantified. And finally, climate change coupled to the likely increases in marine transportation, development of other human uses of marine ecosystems off Alaska, heighten the need for further development of an ecosystem approach to management.

Thank you, Madam Chair, for the opportunity to speak to you today and I would be pleased to answer any questions.

[The prepared statement of Dr. Kruse follows:]

PREPARED STATEMENT GORDON H. KRUSE, PH.D., PRESIDENT'S PROFESSOR OF FISHERIES AND OCEANOGRAPHY, SCHOOL OF FISHERIES AND OCEAN SCIENCES, UNIVERSITY OF ALASKA FAIRBANKS

Introduction

Madam Chair and members of the Committee, it is my honor to testify to you this morning. My name is Gordon Kruse. Since 2001, I have been the President's Professor of Fisheries and Oceanography at the School of Fisheries and Ocean Sciences, University of Alaska Fairbanks. Prior to my current position, I directed the marine fisheries research program for the Alaska Department of Fish and Game for 16 years, where I was the lead Science Advisor to the State of Alaska on state and Federal marine fishery management. I have been a member of the Scientific and Statistical Committee (SSC) of the North Pacific Fishery Management Council (NPFMC's) for 7 years, including the two most recent years as chair (2005–2006) and the two prior years as vice-chair (2003–2004). I served an additional 11 years as a member of the NPFMC's Crab Plan Team and Scallop Plan Team and co-authored the original crab and scallop Fishery Management Plans. I am the current chair of the Fishery Science Committee for the North Pacific Marine Science Organization (PICES), an international marine science organization involving China, Japan, South Korea, Russia, Canada and the U.S.

Objectives of Testimony

My objectives are to discuss: (1) potential mechanisms and effects of climate change on living marine resources in Alaska, (2) future outlook for these resources and implications for management under continued global warming, and (3) uncertainties associated with gaps in our understanding that require further research.

Importance of Marine Ecosystems Off the Coast of Alaska

Alaska is unique in that it is bounded by three large marine ecosystems: the North Pacific Ocean, Bering Sea, and Arctic Ocean (including the Beaufort and Chukchi Seas). These are some of the world's most productive ecosystems, supporting thousands of marine mammals, millions of seabirds, and trillions of fish and shellfish belonging to hundreds of species.

These Arctic and subarctic oceans provide priceless ecosystem services, including human use. Since before recorded history, Native Alaskans have depended on the bounty of these ecosystems for their very existence. Still today, many of these communities remain as subsistence-based (barter) economies, and their harvests of fish, shellfish, mammals and other resources (*e.g.,* bird eggs, kelp) provide the majority of their diets.

These ecosystems support extremely valuable commercial fisheries that provide both U.S. food security and foreign exports that contribute toward the national balance of trade. More than half of the total U.S. fishery landings come from the waters off Alaska. In 2005, landings from Alaska totaled 5.7 billion pounds, representing 59 percent of the total 9.6 billion pounds landed in the U.S. (NMFS 2007). While important fisheries occur in the Gulf of Alaska and Aleutian Islands, most of this catch is taken from the eastern Bering Sea, owing to its broad, highly productive continental shelf. In 2005, the Nation's top seafood port was again Dutch Harbor-Unalaska, accounting for 888 million pounds of landings worth $283 million exvessel (before value-added processing). Moreover, seven of the Nation's top 20 seafood ports are located in Alaska. The Bering Sea supports the world's largest fishery (walleye pollock), largest flatfish fishery (yellowfin sole), and largest salmon (sockeye) fishery. Other valuable commercial fisheries target a diversity of species of crabs, rockfishes, flatfish (flounders and soles), cod, halibut, herring, and other fish and invertebrates. These same waters provide world-class recreational fishing opportunities for non-resident visitors and Alaskan residents alike for salmon, halibut, rockfish and other species.

Resource Sustainability Versus Variability

In their report to the nation, the Pew Oceans Commission (2003) noted that Alaska's fisheries were *"arguably the best managed fisheries in the country. With rare exception, the managers have a record of not exceeding acceptable catch limits set by scientists. In addition, the North Pacific Fishery Management Council and Alaska Board of Fisheries have done more to control bycatch and protect habitat from fishing gear than any other region of the Nation."* The sustainability of groundfish, salmon and other fishery resources in Alaska is tied directly to conservative, science-based fishery management.

Nonetheless, there are clear historical cases of overharvest and resultant collapse of living marine resources, even in Alaska—examples include the Steller's sea cow (hunted to extinction in 1768), northern fur seal (1700s–early 1800s and again in the late 1800s–early 2000s), great whales (mid 1800s–mid 2000s), sea otters (mid 1700s–early 2000s), yellowfin sole (1960s), and Pacific ocean perch (1960s–1970s). Causes of recent declines in Steller sea lions, northern fur seals, shrimp, and king, Tanner and snow crabs are much less clear. Although human effects have been implicated in many of these recent examples and undoubtedly humans have contributed to varying degrees, a large body of scientific evidence has emerged in support of climate change as being primarily responsible for major shifts in the marine ecosystems off Alaska. Environmental variability affecting marine ecosystems occurs over a wide range of time scales; the scales most relevant to most marine animal populations are seasonal to decadal and longer. Owing to our rather short history (few decades) of research and monitoring of marine organisms in Alaska, much of our outlook for impacts of global warming on marine ecosystems is based upon our understanding of the mechanisms and effects operating on shorter time scales, as summarized below.

Effects of Seasonal Climate Variability on Living Marine Resources in Alaska

Seasonal climate variability is vital to the productivity of temperate, subarctic and Arctic marine ecosystems. In these regions, there is a seasonal "battle" between winds that mix deep, nutrient-rich waters into the photic zone and solar heating that warms the upper layers of the ocean, causing thermal stratification that retains microscopic plants (phytoplankton) in the upper layers of the ocean where they can grow under sufficient light penetration and nutrient concentrations.

In the spring, when solar heating wins the battle, an intense bloom of large phytoplankton occurs, providing large amounts of food to microscopic animals (zooplankton) that, in turn, bloom in abundance. This sequential burst in abundance of phyto- and zooplankton serves as food to higher trophic levels, including the planktonic early life stages (larvae) of many commercially important species of fish and shellfish, as well as adults of some species of planktivorous marine mammals (*e.g.,* humpback whales) and seabirds (*e.g.,* crested auklet). In other words, this spring bloom fuels the engine that supports much of the productivity of marine ecosystems in Alaska. The timing of herring spawning, hatching of red king crab larvae, and outmigration of salmon smolts are tied to this remarkable annual event. As summer progresses, nutrients in the warm upper layers of the ocean become depleted, overall production tends to decline, and other species of small phytoplankton adapted to low-nutrient conditions become prevalent.

In the fall, as winds strengthen and solar heating diminishes, the water column mixes, stability breaks down and a smaller fall bloom may occur. However, phytoplankton are mixed to deeper waters where light levels are too low to sustain net growth and the engine that fuels the marine ecosystem slows down. In winter, productivity is low, but, even at this time of year some species (*e.g.,* some flatfish) have adapted strategies for optimum survival as winter spawners. In the following spring, the cycle is repeated again.

Each species has evolved unique life history strategies to be successful in these seasonally dynamic marine ecosystems. For many species of marine fish and invertebrates, their success depends upon the synchrony in time and space of their early life stages (eggs and larvae) with abundances of suitable food, the abundance (or lack thereof) of predators, and ocean currents that carry them (advection) to nursery areas most amenable to their survival. Likewise, the success of seabird and marine mammal populations depends largely upon the ability of adults to secure adequate prey while feeding their young on rookeries.

Effects of Interannual and Decadal Climate Variability on Living Marine Resources in Alaska

El Niño

Although an understanding of seasonal variability in environmental variables is important toward understanding the strategies by which species thrive within marine ecosystems, it is the year-to-year (interannual) variability in climate and ocean processes that determines how animal populations change over time. One important component of interannual variability that occurs every 2–7 years is El Niño/La Niña, an oscillation of a coupled ocean-atmosphere system in the tropical Pacific having important consequences for weather in the North Pacific and around the globe. Prominent features of an El Niño include the relaxation of the trade winds and a warming of sea surface temperature in the equatorial eastern Pacific, extending along the U.S. west coast into Alaskan waters. Species more typical of subtropical and tropical waters extend their distributions into Alaska during El Niño events. For instance, during the 1997–1998 El Niño, albacore tuna were caught off Kodiak Island and ocean sunfish were observed in the northern Gulf of Alaska (Kruse 1998). Global surface mean temperature anomalies provided by NOAA's National Climate Data Center suggest that El Niños became more intense and more frequent in the latter half of the 20th century, quite possibly as a manifestation of global warming. Thus, range extensions and first-time sightings of southern species have become more common in recent years.

Beyond the curiosity of such unusual sightings, more far-reaching marine ecosystem changes can be associated with El Niño events. Coincident with the 1997–1998 El Niño, salmon run failures occurred in western Alaskan river systems imposing severe economic and social hardships in some western Alaskan communities (Kruse 1998). A Federal disaster was declared by the U.S. President. Also, in 1997, the first-ever massive bloom of coccolithophores (a non-nutritious microscopic phytoplankton covered with calcium carbonate platelets) was observed in the eastern Bering Sea. The bloom was so dense and expansive, that it was easily observed by satellites orbiting the Earth. A massive die-off of short-tailed shearwaters was associated with reduced availability of their preferred prey (euphausiids). Murres, a dive-feeding seabird, produced fewer offspring, likely because dense coccolithophore concentrations obscured their vision and ability to feed. It is important to recognize that these ecosystem effects were likely the product of an unusual combination of El Niño, decadal climate variability, global warming, and other atypical regional conditions. However, this suite of climatic conditions set the stage for repeated coccolithophore blooms in the eastern Bering Sea for half a dozen years after this initial event.

Decadal Climate Regime Shifts

Much marine ecosystem research in Alaska since the 1980s has documented decadal climate variability patterns that have led to regime shifts every 10–30 years. The Pacific Decadal Oscillation (PDO) is one index of such shifts, based on warm-cold patterns of sea surface temperature in the northern North Pacific Ocean. Some have likened the warm phase of the PDO to an extended El Niño situation. For instance, ocean temperatures in the northeast Pacific were typically warm in the mid-1920s to mid-1940s, cool during the mid 1940s–late 1970s, and warm since then. The opposite pattern was experienced in the northwestern Pacific.

The regime shift of the late 1970s has been particularly well studied. Since the late 1970s, Alaskan waters have experienced more frequent winter storms associated with an intensified Aleutian Low Pressure System, increased freshwater discharge into the Gulf of Alaska, a stronger Alaska Coastal Current (which flows in a counter-clockwise fashion around the gulf), and warmer ocean temperatures. These changes appeared to have altered the flux of nutrients, leading to a marked increase in the biomass of zooplankton in the Gulf of Alaska. Other major ecosystem changes associated with this regime shift include a decline in forage fishes, crabs, and shrimps and increases in the abundances of salmon and groundfish (Anderson and Piatt 1999). Some research supports the hypothesis that declines in a number of populations of marine mammals and seabirds are related to observed shifts in marine food webs (*e.g.,* decline in forage fish) in Alaska. However, as with any complex ecosystem with limited monitoring, the evidence is less than conclusive.

Decadal-scale variability in the extent of sea ice formation has had profound effects on the Bering Sea marine ecosystem. Sea ice forms and melts seasonally spreading from the northern to southern Bering Sea shelf waters. Timing of the spring bloom depends heavily on ice formation and melt. In years of extensive ice coverage, the ice thaws more slowly and melt water stratifies the upper water column with buoyant, low salinity water. If this stratification occurs sufficiently late (*e.g.,* April), then sunlight is adequate at that time of year to cause an early spring bloom near the ice edge. However, there is a dearth of zooplankton in this cold melt water, so much of the phytoplankton sinks ungrazed to the seafloor where it benefits bottom-dwelling (benthic) species, such as clams, crabs and other invertebrates. On the other hand, in years when ice is thin and less extensive, it melts in February or March; the lesser amount of freshwater is inadequate to stratify the water column and sunlight is too weak at that time of year to support a plankton bloom. In such years, the spring bloom is delayed until May or June after the sun has had sufficient time to heat a stratified layer of warmer water. Warmer ocean temperatures at this time of year support growth of the zooplankton community and much of the phytoplankton production is grazed by water column (pelagic) species, such as walleye pollock.

Sea ice in the southeast Bering Sea has declined markedly from covering 6–7 months in the late 1970s to spanning just 3–4 months each winter since the 1990s. As the ice-edge bloom may account for a large fraction of the total annual primary production in the eastern Bering Sea, there is considerable concern that declines in productivity have occurred with reductions in sea ice since the late 1970s. Although long-term records of phytoplankton are lacking, declines in summer zooplankton have been clearly documented in the eastern Bering Sea by the Japanese research vessel OSHORO MARU since at least 1990.

Effects of Global Warming on Living Marine Resources in Alaska

Terrestrial Impacts of Global Warming in Alaska

Increases in global air and sea temperatures have been clearly documented since the 1800s. On land, observed changes in Alaska are dramatic and well known, including retreat of nearly all glaciers, melting of permafrost and associated structural damage to buildings and roads, and increased insect outbreaks (*e.g.,* spruce bark beetle) in coniferous forests and an associated increase in frequency of forest fires. Along the coast of western Alaska, higher sea levels and lack of shore-fast sea ice in winter has led to extensive coastal erosion during storms, prompting the imminent costly relocation of dozens of Native villages.

Climate and Oceanographic Changes With Global Warming

A composite land-ocean index of global temperature provided by NASA shows that temperature changes since the 1880s reflect the combined influences of the two major frequencies already discussed—El Niños (every 2–7 years) and decadal variability (10–30 years)—plus a long-term increase in temperature associated with global warming (≥100 years). Because our history of research and monitoring of marine organisms is very short (decades) relative to the century-long time scale associated with global warming, the outlook for living marine resources under continued global warming is based largely upon our rather limited understanding of recent variability and mechanisms associated with those observed changes. The outlook for these marine resources also depends upon the accuracy of future projected changes in temperature, precipitation and winds from climate forecast models.

Based on the working group of the Intergovernmental Panel on Climate Change in 2007, the near-term projection is for an average global increase of 0.2° C per decade over the next two decades. The Arctic has been warming twice as fast as the rest of the globe since the mid 1800s, and this accelerated trend is projected to persist for the higher latitudes into the foreseeable future. Based on these IPCC models, increased precipitation is also very likely in the higher latitudes. High-latitude changes in wind patterns are also projected, but specific details in the projections concerning storm frequency and intensity are somewhat less certain.

Shifts in Species Distribution and Abundance

Each species has its own preferred optimum temperatures within a wider range of temperatures suitable for its growth and survival. With warming ocean temperatures, species at the southern end of their distributions (*e.g.,* snow crabs in the southeastern Bering Sea) are expected to contract, whereas those at the northern ends of their distributions (*e.g.,* Pacific hake in southeastern Alaska) are expected to expand northward.

Increased temperatures may benefit some species and disfavor others. With the warming experienced in the last two decades, in-river temperatures in British Columbia have exceeded 15° C, which causes stress in sockeye salmon, increasing susceptibility to disease and impairing reproduction. Studies have shown that mortality is positively related to temperature and river flow in Fraser River sockeye salmon. Turning back to the poor salmon runs in western Alaska in 1997–1998 mentioned earlier, among other potential causes, anecdotal reports found a high incidence of a parasite, called *Ichthyophonus.* Infected fish did not dry properly when smoked (a common means of preservation by subsistence users) and had white spots on internal organs and muscle. Follow-up studies found that 25–30 percent of adult chinook salmon returning to the Yukon River in 1999–2002 were infected (Kocan *et al.,* 2003). Many of the diseased fish appear to have died before spawning. The spread and pathogenicity of this parasite is correlated with Yukon River water temperature in June, which increased from 11° C to 15° C over 1975 to 2002 at Emmonak (river mile 24). Such examples of adverse impacts of increasing temperatures on salmon may become more common in Alaska with continued global warming.

Warming temperatures are expected to increase the northward migration of piscivorous predators into the future. Pacific mackerel and jack mackerel, species common to the coast of California, have extended their distributions into British Columbia in recent warm years. The productivity of Pacific mackerel populations is favored during warm years off California. Mackerel compete with and prey on juvenile salmon; reduced survival of sockeye salmon on the west coast of Vancouver Island is correlated with the abundance and early arrival of Pacific mackerel in British Columbia. The impact of mackerel predation and competition with salmon is a concern for Alaska. Mackerel have already been encountered in Southeast Alaska by salmon troll fishermen.

There are additional concerns about the northward extension of other predators, such as spiny dogfish in Alaska. A colleague from the University of Washington and I have an ongoing project to evaluate the evidence for an increase in dogfish abundance, as well as to evaluate the life history and productivity of dogfish and management implications in Alaska. Bycatch of dogfish is an increasing problem to fishermen, particularly in the salmon gillnet and halibut/sablefish longline fisheries in Alaska. On the one hand, dogfish bycatch causes gear damage (gillnet) and hook competition for more valuable species (sablefish and halibut), but, on the other hand, this species could provide new economic opportunities (dogfish supply the fish and chips industry in Europe). Determination of sustainable harvest levels is problematic for this abundant species that has a low rate of annual productivity associated with delayed maturity and low reproductive rate.

In the Bering Sea, the centers of distribution of adult female red king crab and snow crab have shifted to the north since the late 1960s and early 1970s, likely due to increases in bottom temperature (Loher and Armstrong 2005, Orensanz *et al.,* 2004, Zheng and Kruse 2006). The larval stages of both species are planktonic—subject to passive drift. Given the northward flow of prevailing ocean currents and the probable fixed location of juvenile nursery areas, the northward shift of females has most likely adversely affected the ability of these populations to supply young crabs to the southern end of their distribution in recent decades. At the same time, warming ocean temperatures have allowed predators of young crabs, such as Pacific cod, rock sole, and skates, to shift their distributions to the north. So, the young stages of crab not only have to deal with settlement into suboptimal habitats, but they have to navigate the gauntlet of increased predation by groundfish. These two mechanisms may be leading reasons why crabs have generally faired poorly since the late 1970s regime shift. For these same two reasons, crabs may continue to fair poorly under continued global warming. On the other hand, groundfishes like pollock and cod may continue to benefit.

One species that seems to have benefited greatly from conditions since the late 1970s is the arrowtooth flounder, a species at its highest recorded levels of abundance and still increasing. This species is a voracious predator that consumes large amounts of pollock, cod, and other commercially valuable groundfish and shellfish. Unfortunately, the flesh of the arrowtooth flounder has low market value owing to enzymes that degrade the flesh quality. So, future warm ocean conditions may continue to result in a shift from commercially valuable species, like pollock and cod, to this species, which has low market value.

Other predatory species that may increase in Alaska with continued global warming include seasonal predators, such as albacore tuna. This species would provide new economic opportunities in Alaska, perhaps to the detriment of salmon fisheries.

Restructuring of Ecosystems

Earlier, I discussed the role of sea ice extent on funneling energy to the benthic ecosystem (early spring bloom) or the pelagic ecosystem (late spring bloom). Although the trend since the late 1970s has been toward a late spring bloom favoring pelagic species (such as pollock) in the southeastern Bering Sea, the spring bloom remains largely an ice-edge bloom in the northern Bering Sea, where the ecosystem remains benthic dominated (*e.g.,* clams). This benthic production is essential for a number of charismatic species, such as walruses and spectacled eiders that feed on benthic clams and other bivalves. All, or nearly all, of the world's populations of spectacled eiders overwinter in a small area between St. Lawrence Island and St. Matthew Island in the eastern Bering Sea. In the past decade with an increase in air and ocean temperatures and a reduction in sea ice, there has been a reduction in benthic prey populations and a displacement of marine mammals (Grebmeier *et al.,* 2006). With a commensurate increase in pelagic fishes, the northern Bering Sea is shifting from a benthic to a pelagic ecosystem, posing risks to benthic prey-dependent species of seabirds and marine mammals. This benthic to pelagic trend is expected to increase and expand northward with continued global warming.

Loss of sea ice in the Bering Sea is likely to have major impacts on ice-dependent marine mammal species, such as ring seals and bearded seals. Ring seals excavate caves (lairs) under the ice in which they raise their young for protection from the weather and predators. Ring and bearded seals feed on a variety of invertebrates and fishes. Both seals are major components of the diet of polar bears. Polar bears also have the capacity to kill larger prey, such as walruses, a species with seasonal migrations also tied to the advance and retreat of sea ice. Therefore, it seems very likely that the loss of sea ice associated with global warming will have serious impacts on these ice-dependent marine mammals.

Potential for Invasive Species

An additional area of concern under global warming is invasive species. With increasing ocean temperatures, cold thermal barriers to warm-water invasive species may become removed. One key species of concern is the European green crab, a species that is native to the North and Baltic Seas. Unintentionally introduced as an invasive species, the green crab has consumed up to 50 percent of manila clams in California, and it was blamed for the collapse of the soft-shell clam industry in Maine. This species has the potential to alter an ecosystem by competing with native fish and seabirds. Its recent arrival on the U.S. west coast and potential to expand northward with global warming causes concerns for Alaska with respect to our Dungeness crab fishery and aquaculture farms for oysters and clams.

Changes in Seasonal Production Cycle

Increased temperatures may result in earlier stratification, perhaps advancing the timing of the spring bloom. In such case, the continued success of some species depends upon their ability to spawn earlier so that their early life history stages continue to match the spring bloom. Additionally, greater heat in the ocean may lead to prolonged summer-like conditions favorable to small phytoplankton that thrive in low nutrient conditions, including some phytoplankton species that produce toxins, such as paralytic shellfish poisoning. Food chains based on small phytoplankton (typical of summer) tend to be less productive than those based on large phytoplankton (typical of the spring bloom), because they require more steps of energy conversions along the food chain to support upper trophic level species, such as seabirds, marine mammals, and commercially important fish including cod and halibut. So far, this seasonal cycle outlook is based solely upon increased temperatures; other important considerations are the forecasted future changes in storm frequency and intensity. If greater storminess in the Gulf of Alaska and Bering Sea is associated with global warming, then the increased mixing could somewhat compensate for the tendency for increased stratification caused by warmer temperatures, perhaps resulting in little change in the timing of the spring bloom. However, in such case, given the temperature control of the rate of many physiological processes (including reproduction) of cold-blooded marine fish and invertebrates, a challenge for many species will be to maintain current spawning timing despite warming temperature conditions.

Ocean Acidification

As greenhouse emissions continue to increase, the ocean soaks up more and more CO_2, which when dissolved in water, becomes carbonic acid. Such increases lower the pH of seawater, causing a critical concern for species with calcium carbonate skeletons. Preliminary results of studies in Alaska indicate that declining seawater saturation of calcium carbonate induced by ocean acidification may make it more difficult for larval blue king crabs to harden their shells (J. Short, NMFS, Auke Bay Laboratory, pers. comm.). Juvenile king crabs had substantially increased mortality, slower growth, and slightly less calcified shells when exposed to undersaturated seawater conditions projected for their rearing habitat within the coming century in the North Pacific Ocean. These preliminary results indicate that continued increasing carbonation of the ocean surface layer as a result of increasing atmospheric CO_2 may directly affect recruitment of commercially important shellfish. Other witnesses on this panel have outstanding expertise on ocean acidification and will speak in much greater detail on this topic.

Management and Economic Implications

One need not look further than the Bering Sea pollock fishery in 2006 for an example of the sort of management implications expected under global warming. During the B (fall) fishing season, pollock were farther north and west than normal. Diesel fuel prices were high. The at-sea (factory trawler fleet) sector has the ability to conduct 7–10 day fishing trips and a byproduct of their fish harvests is fish oil, which they burn in their boilers and generators. On the other hand, smaller shore-based vessels only have capacity for 2–4 day trips and they cannot produce fish oil. The northward shift of pollock, typical of expectations under global warming, had relatively small impact on the at-sea sector, but had significant adverse impacts on the shore-based fleet, owing to reduced access to the resource and increased operational costs. Under northward shifts in fish resources, the shore-based fleet will need to shift to a mothership-type fishery or will need to relocate plants in new northern ports at greater investment of capital.

Over the near term, the NPFMC is currently considering management actions with respect to the potential northward expansion of pelagic and other fishery resources into the northern Bering Sea and Arctic Ocean. One major problem is that current surveys do not extend into the northern Bering Sea, much less the Arctic, so allowance of fisheries to follow the fish north would be conducted under increased uncertainty, perhaps at greater risk to previously unexploited benthic resources, which in turn could place sensitive populations of marine mammals (*e.g.,* walrus) and seabirds (*e.g.,* spectacled eider) as risk. At its June 2007 meeting, the NPFMC is scheduled to take action on a proposal to define and mitigate essential fish habitat in the eastern Bering Sea including an SSC proposal to allow fishing in the northern Bering Sea only under an experimentally designed study to test fishing impacts upon which future decisions can be based. Over the longer term, the NPFMC is considering management options for the Arctic Ocean, perhaps under a new Arctic Fishery Management Plan. Management options for the Arctic are constrained by a serious lack of information on the marine fish and invertebrate resources in this region. The reliance of species of marine mammals and seabirds, as well as Native communities, on the living marine resources of these northern areas, heightens the gravity of management decisions for the Arctic Ocean.

Long-term forecasts of the implications of global warming and fisheries management in Alaska are highly speculative, given present levels of understanding. Just as there was a reorganization of marine ecosystems after the regime shift of the late 1970s, marine ecosystems off Alaska might be expected to reorganize again, perhaps to a new unobserved state, in response to a climate regime shift associated with continued global warming. If so, then a commensurate reorganization of the fishing industry is to be expected. Uncertainty increases as conditions (*e.g.,* temperature, percent sea ice cover) move outside the range of historical observations. Under science-based management, increasing uncertainty typically translates into more precaution. Thus, more precautionary management under greater uncertainty, coupled to the increasing use of ecosystem-based fisheries management, will likely result in more conservative fish harvests in Alaska in the future.

Data Gaps and Research Needs

Predictions of future changes of marine ecosystems for the Gulf of Alaska, Aleutian Islands, and eastern Bering Sea are uncertain, partly owing to gaps in our understanding of mechanisms affecting the dynamics of living marine resources and partly due to uncertainties in climate forecast models at the level of detail necessary for the Alaska region. A combination of improved monitoring, process-oriented studies, modeling, and policy development are recommended to improve our ability to forecast and address likely future marine ecosystem changes in Alaska:

- Arctic baselines—very few data are available on the abundance, distribution, and life history of marine species in the northern Bering Sea and Arctic. It is critical at this time to establish baseline understanding of community structure and function before the Arctic region is perturbed by human impacts and climate change.

- Integrated Ocean Observing Systems—establishment of routine observing systems for physical and biological features of marine ecosystems off Alaska is essential to monitoring the effects of global climate change.
- Studies of physiology and life history. Models only go so far; the biology and life history of many species off Alaska are poorly known, including functional relationships between their growth and survival and environmental conditions. In order to understand the effects of global warming and human effects on these populations and associated ecosystem consequences, it is essential to invest in studies of basic biology, life history, and physiology of poorly studied northern marine species. Physiological studies can reveal a great deal about the impacts of increasing temperature on the scope for growth and survival of northern species.
- Coupled climate-ecosystem and climate-fisheries forecasting models. It is imperative to establish explicit linkages between climate forecast models and regional ecosystem and fishery models so that outlooks for changes in marine ecosystems and fisheries can be made more quantitative and less qualitative. In June 2007, PICES will convene a workshop on linking climate and fisheries forecasts, but this is just a very initial step in a process that will require substantial efforts.
- Ecosystem approach to management. Climate change is just one of a suite of both human and naturally occurring factors that need to be considered in the management of living marine resources. Effective management of marine resources off Alaska will become increasingly complex, given the uses of these resources by coastal Native communities and higher trophic level species (*e.g.,* birds and mammals). Potential for increased marine transportation and oil and gas exploration and development further heighten the need for an ecosystem approach to management.

Thank you, Madam Chair, for the opportunity to speak to you and your committee today. I would be pleased to answer any questions you or other committee members may have.

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Senator CANTWELL. Thank you, Dr. Kruse.

Admiral Watkins, welcome. Let me thank you again for your leadership on the U.S. Commission on Ocean Policy, something this Committee has had a lot of involvement with, starting with Senator Hollings' bill on the Oceans Policy Act, and my colleagues Senator Stevens and Senator Inouye and many others have had much involvement in this. We are glad you are back before the Committee.

STATEMENT OF JAMES D. WATKINS, ADMIRAL (RET.), U.S. NAVY; CHAIRMAN, U.S. COMMISSION ON OCEAN POLICY; CO-CHAIR, JOINT OCEAN COMMISSION INITIATIVE

Admiral WATKINS. Thank you very much, Madam Chair and distinguished members of the Subcommittee, for inviting me to participate in today's hearing. I submitted a much longer statement for the record that I hope will be included therein.

I appear before you today representing the interests of the U.S. Commission on Ocean Policy, as well as the Joint Ocean Commission Initiative, which I co-chair with Leon Panetta. As you know, he was Chair of the Pew Ocean Commission, a privately-funded commission. Because we were not doing very much in Washington toward establishing a National Ocean Commission Pew decided to go ahead anyway, which I think scared the Congress and they passed the Ocean Policy Act of 2000, which led to our commission.

I want to thank you, particularly the Senate, for the work that you have done to bring national visibility to the oceans.

While today's hearing is focused primarily on the issue of increasing acidification of the oceans and the impact on living marine resources, I appreciate the opportunity to come and speak to the broader issue of the role oceans play in climate change and the need to pursue strategies, how to mitigate and adapt to these changes.

As public awareness of climate change and its potential economic and environmental consequences has increased, so has the level of urgency to take action. Unfortunately, few people fully appreciate the fundamental role oceans play in governing climate through their immense capacity to store and distribute heat and their part in the carbon cycle. I have never seen one article on climate change that ever mentions the oceans and I think it is a tragedy. They are the first victims and they are also the hope for mankind to come out of this and to adapt to it.

We have global ocean circulation and heat flux models that clearly indicate major changes are under way. Yet we still lack a clear understanding of the underlying dynamics of these processes and are even less knowledgeable about activities occurring along the highly dynamic coastal margins, where ecological and economic activities are of greatest importance to humans and many of the impacts of climate change, such as sea level rise and coastal storms, will be directly felt.

Clearly, a more coherent strategy is needed, and a core element of such a strategy must include increased attention to the role of the oceans and impacts on ocean resources. Let me proceed by focusing my remarks on three key points that I hope my written statement communicates.

Congressional leadership. First, our oceans, coasts, and Great Lakes need a voice and strong leadership and we are counting on the members of this Committee to help fill this role. The ocean community is in the process of a major organizational transition, moving away from an outdated, highly structured, institutional approach toward an integrated process that more closely resembles the function of natural systems. We call that ecosystem-based management.

This transition is necessary in order to respond to the host of problems impacting the ecological health and economic viability of the oceans. These problems range from impacts associated with climate change, such as acidification, sea level rise, more intense coastal storms, to degradation issues such as water pollution, habitat loss, overfishing, and invasive species.

The problems facing the oceans are too large and too varied to continue the current piecemeal approach to management and science. It will take leadership and vision from Members of Congress to lay the foundation for a transition to ecosystem-based management. It will be difficult and require some painful decisions, but it is incumbent upon you to recognize the need for reform and to move the process forward, and today's hearing hopefully is a major step toward this objective.

Governance reform. My second point builds squarely on the concerns raised in my first point. Governance problems in the oceans community are severely limiting the oceans community's capacity to provide the scientific information and management options needed by Congress to make critical policy decisions. Given the oceans' fundamental role in climate change, this weakness in the ocean community is impacting its capacity to make meaningful contributions toward the effort to understand and address climate change.

We need a new governance regime within the Federal Government that moves away from the stove-piped, command and control organization where the budget process often discourages interagency cooperation. The Joint Initiative has made ocean governance reform one of its highest priorities and the urgency of this issue has only escalated, given the need to address ocean-related science and management demands associated with climate change.

We must focus on improving our capacity to more accurately assess the processes influencing climate change and place greater attention on designing and implementing a comprehensive strategy that balances resources across the spectrum of scientific disciplines, that is physical, chemical, and biological, and sectors, that is research, monitoring, and modeling, as well as expand support for translating this data into information that will allow you, Congress, to establish policies aimed at meeting the goal of improving the resiliency of the coastal communities and ecosystem.

My final point is straightforward: The time to act is now. Leon and I are committed to pursuing the implementation of the two Commissions' recommendations through establishment of the Joint Initiative because we feel strongly that a failure to respond to problems facing our oceans and coasts now will result in irreversible damage to our economy and environment. The urgency of the need for action is further highlighted by growing concern over impacts associated with climate change and the ocean's role in the process.

A much more comprehensive and robust science enterprise, one that includes a better understanding of the ocean's role in climate change, is required to more accurately predict the rate and implications of change at the global through local level, as well as to enable a more thorough evaluation of options for mitigating and accommodating this change.

One of the first steps in the process of strengthening the science enterprise should be a commitment to building a comprehensive environmental monitoring system. Clearly, an integrated ocean observing system such as the one recommended in Senate 950, which is cosponsored by many members of this Subcommittee, should be a key element of such a system.

Yet progress toward this goal is limited and appears to be moving backward. A recent NRC study out of the National Academies found that remote sensing satellite programs of NASA are at serious risk due to a $500 million decrease in funding for its Earth Science program and that the next generation of satellites on the drawing board are generally less capable than the current, rapidly diminishing system.

This situation must be addressed and a comprehensive monitoring system that includes support for data management and analysis and modeling must be the core of a national strategy.

I will conclude by noting that the recent elevation of concerns surrounding climate change and its economic and environmental implications validate similar concerns voiced by the oceans community in the release of the U.S. Commission on Ocean Policy and Pew Ocean Commission reports. At the heart of the matter is the need for a more robust science enterprise capable of advancing our understanding of the processes that drive our planet and guide the decisions of policymakers. The integration across agencies and scientific disciplines can only occur if we succeed in implementing a new governance regime that facilitates greater collaboration, including resources and expertise outside of the Federal system.

So I am appealing to you publicly, as Leon and I have done in private, to take up the mantle of governance reform in the ocean community. It is the critical first step in a process toward realigning and focusing the resources and energy of the ocean community toward restoring the health and viability of our oceans and coasts. I can assure you that the rewards will be immense and enduring and will provide you with a lasting legacy.

Thank you for the opportunity to appear and I stand ready to answer your questions.

[The prepared statement of Admiral Watkins follows:]

PREPARED STATEMENT OF JAMES D. WATKINS, ADMIRAL (RET.), U.S. NAVY; CHAIRMAN, U.S. COMMISSION ON OCEAN POLICY; CO-CHAIR, JOINT OCEAN COMMISSION INITIATIVE

Madame Chair, Senator Snowe and members of the Subcommittee: Thank you for the invitation to testify at today's hearing. I appear before you today representing the interests of the U.S. Commission on Ocean Policy as well as the Joint Ocean Commission Initiative, which I co-chair with Leon Panetta. The Joint Initiative is a collaborative effort of members of the U.S. Commission on Ocean Policy and the Pew Oceans Commission. The purpose of the Joint Initiative is to advance the pace of change for meaningful ocean policy reform.

Leon and I believe that this is an important hearing and hopefully is the first of many hearings that will examine the fundamental role oceans play in global climate change, as well as the impact climate change is having on our oceans and coasts. We trust that the Members of the Committee will work closely with the multitude of other congressional committees that share jurisdiction over climate change related issues and will champion the need for greater attention to governance needs and the commitment of resources to support ocean-related science, management, and education.

Multi-jurisdictional problems, such as climate change, are becoming more common. In the work of our commissions, we found almost the identical problem in the effort to deal with the many problems facing our oceans, coasts, and Great Lakes. The lack of governance regimes capable of reaching across the diversity of congressional committees and Federal agencies is severely hampering our capacity to deal with these issues. Thus, while I understand that today's hearing is focused on the issue of the increasing acidification of the oceans and the impact on living marine resources, I appreciate the opportunity to speak to the broader issue of the role of oceans in climate change and the importance of pursing strategies *now* to help coastal communities adapt to the inevitable changes that will occur in the coming years.

Oceans Role in Climate Change

As public awareness of climate change and its potential economic and environmental consequences has increased, so has the level of urgency to take action to mitigate the causes of this change and to make preparations to adapt to its impacts. Unfortunately, few people fully appreciate the fundamental role oceans play in regulating climate through their capacity to store and distribute heat and their role in the carbon cycle. As a nation, we are even less knowledgeable about the ramification of this change on the health of coastal and pelagic ecosystems and their capacity to provide the services upon which we've come to rely. This lapse has resulted in limited understanding of the complexity of ocean-related physical, geochemical, and biological/ecological processes that are influencing and being influenced by the ongoing change. The consequences of this lack of knowledge are significant. Policymakers struggle to evaluate alternatives to address climate change because the levels of uncertainty associated with the short- and long-term impacts of proposed options are relatively high and the science underpinning these decisions is inadequate. Clearly, a more coherent strategy is needed to address climate change, and a core element of such a strategy must include increased attention to the role of the oceans.

Oceans are key drivers in the Earth's heat and carbon budgets, storing one thousand times the heat of the atmosphere and absorbing a third of all anthropocentric carbon dioxide generated over the last few centuries. Furthermore, oceans not only store heat, but transport it around the globe, as well as vertically through the water column in ocean basins, making it a driving force of climate change. While our knowledge of physical oceanographic processes is further advanced than that of geochemical and biological processes, it is still rudimentary due to the lack of a comprehensive monitoring regime. As a result, we have ocean circulation and heat flux models that clearly indicate major changes are in progress. However, we still lack a clear understanding of these processes on a global scale, and are even less knowledgeable about activities occurring along the highly dynamic coastal margins, where ecological and economic health are of the greatest importance to humans and many of the impacts of climate change—such as sea level rise and coastal storms—will be directly felt.

Further complicating the situation is the lack of understanding of the interrelationship among the physical, geochemical, and biological processes. As today's hearing clearly demonstrates, we need to know the implications of ocean acidification on marine ecosystems—such as phytoplankton communities, coral reefs, and fish larva. We also need to know the rate of ice sheet melt and its impact on coastal communities, polar ecosystems, and regional weather patterns.

The complex relationship between oceans and climate change, as we currently understand it, cries out for reform in two core areas, governance and science. Congress must respond to the chorus of criticism directed at the lack of a coherent strategy and framework for addressing the challenges facing our oceans and coasts. This strategy, in turn, must be integrated into a broader national initiative to deal with climate change. It is incumbent upon Congress to take this opportunity to look beyond parochial interests and issue-specific legislation, and work toward a governance regime and management policies that place greater emphasis on cooperation and collaboration within the Federal Government, while capitalizing on the wealth of scientific expertise and resources that reside outside the Federal system.

Governance

The complexity and breadth of issues associated with efforts to understand, mitigate, and adapt to climate change make it essential that the Nation have a coherent and comprehensive strategy to guide this work. This is a daunting challenge given the multitude of governmental and nongovernmental entities that have a vested interest in this issue and its long-term impact on the health and viability of the nation's economy and environment. The ocean community has been struggling with this same problem, albeit on a slightly smaller scale. But the challenge remains the same, we need a new Federal governance regime that moves away from the stove-piped, command and control organization in which individual departments and agencies formulate policies and budgets that are reviewed by the Office of Management and Budget and then sent to Congress for a similar review by the appropriate committee of jurisdiction. While there is a continuing effort to integrate programs and activities, it is the exception not the rule. In addition, the budget process often discourages interagency cooperation as funding for multi-agency programs is subject to cuts or reductions during internal agencies budget negotiations, compromising the integrity of the broader strategy and promoting further competition among Federal and non-governmental players.

But don't take my word for it. There are a number of credible entities that have recognized that governance problems are impeding the Nation's capacity to respond to some of its most pressing challenges and have recommended solutions. Earlier this spring the National Research Council (NRC) responded to a request from the White House Climate Change Science Program to identify lessons learned from past global change assessments. In its report, the NRC cited the lack of a long-term strategic framework for meeting the climate change research mandate as an outstanding weakness of the current system.[1]

Testimony by former administration officials who oversaw the climate change research program reiterated these concerns last Thursday in a hearing before a House Energy and Commerce Subcommittee, where recommendations were made to establish a program office with a sense of permanence, the political power to make decisions across agencies, and the authority over budgets.[2] These recommendations closely track those made by the two ocean commissions, which advocated for a new management regime, based in the Executive Office of the President that would have the authority to coordinate efforts and guide the distribution of resources throughout the Federal Government in an integrated system that reached across jurisdictional boundaries of individual agencies.

Such a vision was partially implemented in the ocean community when the President established the Committee on Ocean Policy (COP). However, the COP's charge is limited to coordination. It lacks institutional independence and a leader charged with resolving interagency disputes and representing the interest of individual agency ocean programs in the budget process. Consequently, efforts to move a new national ocean policy forward have languished and the ocean community's capacity to contribute toward the scientific and management needs to address climate change have been compromised.

Similar problems exists in Congress, where cross-cutting issues such as oceans and climate fall under the jurisdiction of multiple committees and subcommittees. Take the case of ocean acidification. The Commerce Committee clearly has jurisdiction; however, the Environment and Public Works Committee has authority over water pollution and water quality issues, the Energy and Natural Resources Committee has a role regarding emissions from energy facilities, which are a major source of CO_2, and the Committee on Appropriations funds authorized activities. The same diversity of oversight authority exists in the House, significantly complicating efforts to develop a comprehensive strategy to address climate change. In the 108th Congress, the U.S. Commission on Ocean Policy identified a total of 58 standing committees and subcommittees having jurisdiction over ocean-related issues in the House and Senate.[3] An early assessment of the 110th Congress shows little change or consolidation.

Further evidence of support for a more coherent approach to science-related policy issues is reflected in the growing interest in reestablishing an Office of Technology Assessment (OTA). OTA was a congressional office charged with providing non-partisan research on technical and scientific issues pending before Congress, but was closed in 1995. As Congress struggles with increasingly sophisticated and complex technical issues such as biomedical research and climate change, an entity such as OTA can provide timely and issue specific guidance that would complement the more exhaustive, costly and time consuming review process performed by the National Academies. Congress relies on credible and readily available information to make informed policy decisions. Right now, the lack of information on oceans and coasts, or a clear strategy for collecting and translating this information into prod-

[1] Analysis of Global change Assessments: Lesson Learned. National Research Council 2007.

[2] Hearing before the House Science and Technology Committee, Subcommittee on Energy and the Environment; Reorienting the U.S. Global Change Research Program Toward a User-Driven Research Endeavor. *http://science.house.gov/publications/hearings_markups_details.aspx?NewsID=1798* May 3, 2007.

[3] U.S. Commission on Ocean Policy, Appendix F. 2004.

ucts and services useful to decisionmakers and managers, is hobbling Congress' ability to perform its role.

Thus, the focus must turn to improving our capacity to more accurately assess the processes and phenomena influencing climate change and society's impact on such processes and phenomena. This will require much greater attention and support being devoted to the broader problem of designing and implementing a strategy that balances resources among basic and applied research, monitoring and analysis, and modeling. This strategy must also be expanded to incorporate support for translating and utilizing this information to evaluate the effectiveness of mitigation, adaptation, and other management actions aimed at meeting the goals of increasing the resiliency of coastal communities and ecosystems.

Given the complexity and interdisciplinary nature of the issues surrounding climate change, progress toward these goals will require changes in the operation and coordination of Federal agencies and the Federal budget process. The National Oceanic and Atmospheric Administration (NOAA) is the logical lead Federal agency to oversee the climate change science program; however, public and private confidence in the agency is lacking. This is due, in great part, to the outdated organizational structure of the agency and the lack of resources that have been provided to fulfill its expanding mandate. The opportunity is ripe to reevaluate and realign NOAA's programs along its core functions, which include: assessment, prediction and operations; scientific research and education; and marine resource and area management. This step, taken in combination with an effort to enhance the oversight role of the President's Committee on Ocean Policy, would lay the foundation for a major transition in the ocean and atmospheric policy that would be of enormous long-term benefit to Congress and the public.

Congress should also take advantage of this opportunity to address science agency mission and funding inconsistencies that are hampering the collection and synthesis of long-term data measurements. While NASA and NSF are charged with developing new approaches to collecting, analyzing, and integrating data, NOAA has the charge—but lacks the technical expertise and fiscal resources—to maintain increasingly important remote and *in situ* observation platforms capable of sustained data collection (the compilation of long-term data sets). These long-term data sets are crucial to understanding the rate of change over an extended period. Further exacerbating the situation is a disjointed data management system that is preventing scientists from fully utilizing data that are currently being collected. Given the consolidation of science agencies (NOAA, NASA, and NSF) responsible for ocean and atmospheric research under the jurisdiction of the Commerce Committee and its sister appropriations subcommittee, the opportunity exists to more closely link their complementary programs through both the authorization and appropriations processes. While this proposal may disturb many of those in the community who have a vested interest in programs associated with the individual agencies, in the long-term their collaboration is essential if our Nation is to succeed in making progress toward understanding and responding to climate change while also restoring the health of our oceans and coasts.

Clearly, a careful reevaluation of the governance regime guiding climate and ocean-related science and management programs is needed to overcome the obstacles that are currently hampering efforts to develop a comprehensive response to climate change. Whatever action Congress takes, it should look beyond the current models and existing organizational structure to ensure that both ocean and climate change programs are broad-based and charged with developing a balanced strategy that incorporates science, management and outreach. Anything less will perpetuate an approach that has proven to be ineffective and is now jeopardizing the health and welfare of current and future generations.

Science

Credible scientific information is essential as the Nation begins the process of developing a new regime to mitigate and adapt to climate change. Better science, when linked with improved risk management and adaptive management strategies will help guide a process that must deal with the relatively high levels of uncertainty surrounding mitigation alternatives and the range of impacts associated with climate change. A much more comprehensive and robust science enterprise—one that incorporates a better understanding of the oceans' role in climate change—is required to more accurately predict the rate and implications of change at the global-through-local level, as well as to enable more thorough evaluation of options for mitigating and accommodating this change.

While the United States is making a significant financial commitment to understanding climate change, the inadequacy of the current strategy has become clear and reform is urgently needed. Research that has been primarily focused on physical science and validation of climate change must expand to incorporate greater attention to the role and contributions of biogeochemical and ecological processes, as well as interactions among these three processes. This will require a significant commitment of new resources and will increase the complexity of the science strategy to understand and respond to climate change. However, these actions cannot be avoided if the science community is going to be responsive to Congress' need for credible scientific information to guide its decisionmaking process.

One of the first steps should be a commitment to building a comprehensive environmental monitoring system. We are supposedly well on our way to fulfilling our international commitment to support *climate* observing systems—which according to the most recent report from the Climate Change Science Program is over 50 percent complete. However, support for this system is in trouble, which is compounded by the fact that considerably fewer resources are dedicated to supporting an *ocean-focused* component of the observing system. A recent NRC study found that remote sensing satellite programs in NASA are at great risk and that the next generation of satellites is generally less capable than the current, rapidly diminishing system. Projected budgets show U.S. investment in these capabilities falling by 2012 to its lowest level in two decades.[4] Support for a dedicated ocean observing program appeared in the President's budget for the first time this year, at the level of $16 million, a fraction of what Congress has been providing in recent years.

As a consequence our knowledge of physical ocean-related processes is limited, and our capacity to understand biogeochemical and ecological processes languishes due to the lack of capacity to study, much less monitor and model these systems and their responses to change. The expert scientific witnesses appearing before the Subcommittee today have testified to this fact, presenting us with quantifiable data that humans have contributed to the increased acidification of the oceans and that there are very real and potentially damaging consequences associated with this change. Yet, the ocean scientific community does not have access to funding to support large-scale field experiments, study environments that are naturally more acidic, or more fully examine the geologic record to understand past events that may have resulted in similar conditions.

It is now obvious that enhanced and integrated observing systems are a key element underlying a robust ocean and climate science strategy. From a research perspective this need was clearly articulated in the release of the Administration's *Ocean Research Priorities Plan and Implementation Strategy* in January, in which the deployment of a robust ocean-observing system was highlighted as a critical element of the plan. Such an observing system will require a commitment to deploy and maintain infrastructure and instrumentation, such as satellites, research vessels, buoys, cabled underwater observatories, and data management networks. A sustained, national Integrated Ocean Observing System (IOOS), backed by a comprehensive research and development program, will provide invaluable economic, societal, and environmental benefits, including improved warnings of coastal and health hazards, more efficient use of living and nonliving resources, safer marine operations, and a better understanding of climate change. However, the value of this system will be fully realized only if an adequate financial commitment is also provided to support integrated, multidisciplinary scientific analysis and modeling using the data collected, including socioeconomic impacts. Unfortunately, support for the lab and land-based analysis of the data derived from these systems is often inadequate, diminishing the value of these programs, while support for socioeconomic analysis is virtually nonexistent.

The lack of a comprehensive climate change response strategy and supporting governance regime that integrates fundamental research and development, monitoring and analysis, and modeling efforts is a major weakness in our national effort. It must be immediately addressed to ensure that policymakers have the scientific information necessary to guide their deliberation regarding both mitigation and adaptation strategies. Congress should develop legislation, perhaps with guidance from the National Research Council, requiring the development of a comprehensive science strategy that incorporates support for ocean-related sciences with a focus on enhancing the predictive capacity of physical and ecological models. This advancement is necessary to provide policymakers and the public with the information necessary to make informed decisions regarding the collateral impact of potential mitigation strategies—such as carbon sequestration in or under the oceans or biofuel production that results in increased runoff of agricultural pollutants into coastal watersheds—and strategies for increasing the resiliency of coastal communities and marine ecosystems to climate generated impacts.

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[4] Earth Science and Applications for Space: National imperatives for the Next Decade and Beyond, NRC 2007.

Conclusion

The recent elevation of national conversation surrounding climate change and its economic and environmental implications validate similar discussions voiced by the ocean community upon the release of the U.S. Commission and Pew Commission reports. At the heart of the matter is the need for more a robust science enterprise capable of advancing our understanding of the processes that drive our planet and can better guide the decisions of policymakers. The integration across agencies and scientific disciplines, with a focus of developing products and services useful to policymakers and the public, will only occur if we succeed in implementing and integrating new governance regimes for climate change and ocean policy that facilitates greater collaboration, including resources and expertise outside of the Federal system.

This transition must be well thought out and deliberate, perhaps pursuing a phased approach such as that recommended in the U.S. Commission report. In it, we recommended that the initial focus be on strengthening NOAA, followed by a realignment and consolidation of ocean programs that are widely distributed throughout the Federal Government. The final phase would be the consolidation of natural resource oriented programs under a single agency. This approach responds to the recommendation of the Volker Commission, which identified the proliferation and distribution of agencies and programs throughout the Federal Government as a major hindrance to efficiency and effectiveness of the Federal system.[5]

I am appealing to you publicly, as Leon and I have done in private to many of you, to take up the mantle of governance reform in the ocean community. It is the critical first step in the process toward realigning and focusing the resources and energy of the ocean community toward restoring the health and viability of our oceans and coasts. I understand it will be difficult, but increased public awareness and concern about the health of the environment has provided us with a unique and timely opportunity to leave a lasting legacy, one we can appreciate when sitting on a beach—free of closure and swimming advisory signs—on a sunny summer afternoon with our children or grandchildren while looking out over the horizon of a sparkling blue sea.

Madame Chair and Members of the Subcommittee, I appreciate the opportunity to appear before you today, and look forward to working with you to address the ocean and coastal issues raised in this hearing. I would be happy to answer any questions that you may have.

Senator CANTWELL. Thank you, Admiral Watkins. Thank you for your, as I said earlier, ongoing advocacy in this area.

We will start now with a round of 5-minute questions from my colleagues. I will start off with Dr. Feely if I could, asking you a question about this experience of acidification that we are in now. Obviously, we have had other experiences in the past on ocean acidification.

We obviously—I do not know if you are anticipating my question.

[Laughter.]

Dr. FEELY. If that is the question, I have a slide for you.

Senator CANTWELL. I did not know I was going to ask this question. But we obviously have had time periods before between glacial and inter-glacial periods when we have had acidification. So what is different now? That is my first question. If you have a slide for that I am going to be very surprised.

[Laughter.]

Dr. FEELY. Actually, no. In the past, through the geological past, the CO_2 levels have been much higher than we have seen now, perhaps 20 million years ago or even farther back. The difference is that the organisms that are responding to the acidification respond to the saturation state of sea water, which is a combination of the CO_2 concentrations and the pH change and the calcium changes.

[5] National Commission on the Public Service: *Urgent Business for America: Revitalizing the Federal Government for the 21st Century http://www.brookings.edu/gs/cps/volcker/volcker__hp.htm* 2004.

It turns out that in our present condition calcium concentrations are lower than they have ever been in geological history. So therefore the saturation state that we are looking at occurring in the future is going to be lower than has ever been observed in the geological past. This is being influenced directly by the CO_2 increases that we are observing.

So these ecosystems will be looking at a lowered saturation state that has not been observed through the entire history of the oceans.

Senator CANTWELL. So how should we look at the corrective nature of things in the context if we were able to reduce CO_2 emission now how long would it take to have an impact? How do we look at the time period if we continue for another 10 years at the level of CO_2 emissions? We have heard from Dr. Hansen and Admiral Watkins about various adaptive or ecosystem approaches. How do we look at what we can do to correct this current trend?

Dr. FEELY. That is very difficult to answer, particularly because we do not have a lot of information on what the biological tipping points are for these individual species. We do for a select few species that have been studied in mesocosm experiments under laboratory and bag experiments in the field. These tipping points suggest that by the middle of this century the coral reef systems will be severely impacted by the increasing CO_2 levels in the oceans.

The concern that we have is in the ocean itself, the reefs are not only influenced by these simple relationships that we just determined in the laboratory, but also other impacts such as erosion, storm effects, and perhaps the tipping points that we measure in the laboratory do not show and represent what the organisms see in the field.

So what we dearly need is experiments that occur in the field that are representative of field conditions, as well as continuing experiments in the laboratory. Our best projections right now are that for coral reef systems we may be seeing severe impacts as soon as 2050 or earlier.

Senator CANTWELL. Dr. Kruse, how do you as an expert in fisheries management, how do you deal with this information? I mean, are you working into, with salmon or Bering Sea species, are you working factors of climate change and acidification into the management plans for fisheries? How do you address that if, as Dr. Feely says, we do not have all the data, but we know that we are starting to see impact?

Dr. KRUSE. Thank you for your question. In the North Pacific Fishery Management Council, we are making some really pretty good progress to incorporate climate variability into fish stock assessments and fishery management. One of the ways that scientists are doing that, for example, is they have found that the catchability of the trawl used to survey of certain species is very highly dependent on temperature. So they have done experimentation both in the field, but also modeling studies, that have identified the nature of that relationship. So they are incorporating that into stock assessments.

Also, with the Bering Sea pollock, which is probably the best assessed fish stock that we have in our system, there has really been some excellent studies relating the dynamics of that particular population to temperature and sea ice dynamics. So those are finding their ways into the management strategies.

Admittedly, we are really early on the curve of doing this. In fact, soon there will be a workshop to address these issues. I chair the Fisheries Science Committee for the PICES, the North Pacific Marine Science Organization. A subgroup of us are having a workshop in Seattle in July 2007 with our international Pacific Rim colleagues to see how we can better make these connections between climate and our fish assessment models and our management strategies.

So we are making some progress, but certainly there is a lot more work to be done.

Senator CANTWELL. Well, I applaud the North Pacific Fishery Management Council for its leadership in this area. I think in the past you have showed great stewardship on environmental issues, so I applaud that, even though it seems challenging at this point in time.

Senator Stevens?

Senator STEVENS. Thank you very much.

Mr. Doney, I am informed that the Pacific Decadal Oscillation has shifted every 20 to 30 years and that if we look at the past there were temperature observations that the ocean cooled from 2003 to 2006, but over the past 40 years that the average of all those has been that the warming trend has resulted in a .04 degrees change Centigrade. Do you agree with that? The increase in the temperature of the oceans has been .04 degrees Centigrade?

Dr. DONEY. Senator, I think that is a reasonable estimate of the volume average change. That is actually a rather large number. The heat capacity of the ocean is several thousand times that of the atmosphere, and the numbers, the back of the envelope calculation, is that if the integrated global average temperature of the ocean went up by .1 degrees it would be equivalent to the atmosphere going up by 100 degrees.

So you have to think about it in the context——

Senator STEVENS. That is in terms of stored heat.

Dr. DONEY. That is in stored heat.

Senator STEVENS. I understand that. But in terms of the temperature, the implication of your testimony was there has been this overwhelming rise in the temperature of the oceans. Is that your position?

Dr. DONEY. The surface temperature has been going up about .2 degrees per decade over the last 30 years, and if you look at the full water column much of the heating is occurring at the surface. As you go down the water column, the heating rates are smaller, but they are quite large relative to the natural background.

Senator STEVENS. You disagree with that figure that I just gave you, then, that the average for 40 years is .04?

Dr. DONEY. I think it is .04 degrees Celsius over the 40 year period. That is actually quite a large number, considering the rates that the ocean heats and cools naturally.

Senator STEVENS. Do you agree or disagree, doctor? Is that a proper figure?

Dr. DONEY. I would have to check my numbers, but I think that is a reasonable estimate.

Senator STEVENS. I have been told that we are ending the Little Ice Age, that this period we are seeing right now is a return to the normal situation at the beginning of that Little Ice Age. Do you disagree with that?

Dr. DONEY. I do think the paleoclimate data suggest that the current temperatures are much higher than the temperatures that were existing before the Little Ice Age. These are records that are based on, for example, tree ring records and isotope records. The best estimates of the climate over the last thousand years show that the 50-year period we are in now is warmer than at any time in the last 1,000 years.

Senator STEVENS. How long do you think the Little Ice Age lasted?

Dr. DONEY. The Little Ice Age was a couple hundred years. So we are certainly experiencing much warmer climate than existed prior to the Little Ice Age.

Senator STEVENS. Would you check that, please, because that is not my information.

Dr. DONEY. I can check that for you, sir.

Senator STEVENS. Let me ask Admiral Watkins. I think I agree with everything you said. The difficulty is the funding. Since 2001 the Congress and this administration has allocated $29 billion just to climate-related science alone. There may be some question of whether those funds were spent effectively, but that is a massive increase over the previous 6 year period.

How much more do you think we need to have?

Admiral WATKINS. Senator, last year we worked with the staff up here and members to deliver the answer to some questions raised by the Senate, and I think you were a co-signer on that letter.

Senator STEVENS. Yes.

Admiral WATKINS. We worked very hard on that to come up with what do you need, what are we talking about here? We came up in that report, "From Sea to Shining Sea," that the Senate acted on last year, at least in one case, and that was Magnuson-Stevens Reauthorization Act. That was a good product that came out of that.

That was the Senate. You had to push it through the House. We have not had any support from the House on funding. In fact, the Senate has had to restore every year for the last 5 years significant cuts by House Appropriations, coming over here with NOAA getting a $500 million cut, and you have had to restore it all.

So we have spent all our time restoring to status quo. And our report said status quo ain't good enough. We have got to start making the investment in science. We have got to start getting serious about organization and structural changes of how we deal with an ecosystem-based approach that cuts across jurisdictional lines both in the White House and up here and in the states. And we still have not done anything. So it has been 3 years now.

So I am just saying I count on the Senate because the Senate has been the only receptive body, and we have not put enough money in. We said $750 million over 2007 appropriated is the right kickstart, and to do that for the next 4 or 5 years to try to buildup to about $13 billion——

Senator STEVENS. I wanted that in the record. $750 million, if we had that increase by that amount over 5 years——

Admiral WATKINS.—over 5 years that would do everything we recommended in our report, and that would include the climate change issue.

Senator STEVENS. Madam Chairman, I have a conflict. May I ask one more question?

Senator CANTWELL. Yes.

Senator STEVENS. Dr. Kruse, I do appreciate your coming, as I indicated. I want to know this. I am told, and as a matter of fact you said in your own testimony here today that is printed, that the North Pacific temperatures warmed between 1920 and 1940. Do we have any records to show what happened to king crab and other species during that time? Did they shift northward during that period, that 20 years of warming? Can we show—when the temperature went down, were they restored naturally?

Dr. KRUSE. Thank you, Senator Stevens, for your question. That is really an excellent question. Unfortunately, as we go back in time we find we just do not have the routine stock assessments that we have now. For example, in the Bering Sea the very first National Marine Fisheries Service bottom trawl survey started, I believe it was 1969, and it was in a small area of Bristol Bay, focusing on Bristol Bay red king crab.

Likewise in the Gulf of Alaska, most of our surveys started in the 1980s or maybe in the 1970s. So we do not have the fishery-independent information to really objectively look at that question. If you look at fisheries data, you always have to be careful because catch rates can be affected by fishing practices and there may not be a direct reflection to what the populations are doing.

In the Kodiak area, for example, those fisheries did not begin until the late 1950s and really got under way in the 1960s. King crab catches peaked in 1965. So we just did not have observations prior to that time.

There were, however, some fishermen who were fishing for other species who claim that in the earlier time period it was very rare to find king crab. So it is anecdotal information that lends support that crab populations were down.

Senator STEVENS. Did those peaks follow the temperature curve, is what I am getting at? Have they followed the temperature curve? There seems to be a 20 year up and 20 year down in the North Pacific. Have the peaks in our species followed that curve?

Dr. KRUSE. The short answer is some of them do and some of them don't. I spend a lot of time with colleagues examining crab population dynamics and some crab populations seem to be related to temperature signals. The northern shrimp that had supported a big fishery in Alaska is more clearly related to temperature, particularly in the North Atlantic. But it is difficult to simply connect temperature to king crab population dynamics. It is much more complicated.

Senator STEVENS. I thank you. I have overstayed my leave. I saw a chart just recently that showed that the CO_2 spike was very small compared to the spike in methane. We have now got enormous amounts of methane being released from the permafrost in

Russia and in the Arctic. Has anyone examined this? Is that going to affect the oceans at all as the methane continues to increase?

Dr. KRUSE. I have not done that. It is not my area.

Dr. DONEY. I will take a shot at that. Molecule for molecule, methane is about 20 times or 30 times more potent as a greenhouse gas than CO_2.

Senator STEVENS. Why have we not measured that, then?

Dr. DONEY. Actually, there is a global network that NOAA is part of that measures methane, and there are actually quite good measurements.

Senator STEVENS. I mean in relation to the oceans.

Dr. DONEY. The effect of methane on the oceans is, as I mentioned in my testimony, is one of the other greenhouse gases that is leading to increased warming. The methane doesn't dissolve in the ocean, so most of its impacts are through increased warming.

Senator STEVENS. Thank you very much.

Senator CANTWELL. Dr. Feely, did you want to respond to that too?

Dr. FEELY. I just wanted to add that when methane is released into the oceans it quickly oxidizes to CO_2 by bacterial processes. So the impacts that we see in the oceans are the oxidation product of CO_2.

Senator STEVENS. Resulting from the increase in methane?

Dr. FEELY. When methane is released, for example from sediments or from methane hydrates, it quickly gets oxidized to CO_2 by methane-oxidizing bacteria. So the impacts that we would see in the oceans would be the CO_2 enrichment.

Senator CANTWELL. Thank you.

Senator Klobuchar?

Senator KLOBUCHAR. Thank you, Madam Chair.

I just wanted to follow up, Dr. Doney, on some of the questions that Senator Stevens was asking about the temperature issue, just to clarify this. I am also on the Environment Committee and I get questions about this kind of thing a lot. I always use the example for the air temperature that it has gone up one degree in the last century and the EPA predicts it will go up 3 to 8 degrees in this coming century. To give some perspective to people, because especially in Minnesota we think, well, in the middle of the winter that does not sound that bad, but I give them the perspective that since the Ice Age it has only gone up 5 degrees, the height of the Ice Age, the temperature worldwide.

So I wondered if you could use that kind of analogy with the ocean temperatures in some way to better clarify this for us, when you said that it was actually a large amount to go up .04.

Dr. DONEY. Right, and I also wanted to make one additional clarification, which is there were some early reports that global ocean temperatures had started to drop around the year 2002. But when they went back and reexamined the data, they found that they had been making errors in the way they had been treating some of the data. The most recent estimates are that the ocean temperatures leveled off or cooled slightly but there has not been a significant, long-term drop since the observational record began.

Yes, the ocean changes that we are seeing are unprecedented in the historical record and are comparable to what was seen during the deglaciation from the last glacial period. You have to remember, though, when you are talking about the temperature change of 5 degrees between the glacial maximum and what we call the Holocene, the modern period, that occurred over several thousand years. We are experiencing the same temperature change over decades, and that is what I mentioned in my testimony that it is not just the magnitude of the change, it is the rate of change that species cannot adapt to.

Senator KLOBUCHAR. Thank you.

One of the things I get asked about is the effect that this has had on the severity of storms with the warming of the ocean. Does anyone want to lend some expertise to that issue?

Dr. DONEY. I will try to answer that. There is some data that suggests that the intensity of tropical storms has been increasing for things like hurricanes and typhoons. There is still not clear evidence whether the frequency of storms will change. There are good theoretical reasons to believe that storms will increase in intensity because warmer air can hold more water, and the whole process of the energetics of warmer sea surface temperatures and warmer atmospheres holding more water should lead to stronger storms, both in the tropics, but also at mid-latitudes, which could lead to not just effects in the ocean, but effects on land like increased flooding.

Senator KLOBUCHAR. I mentioned the Great Lakes earlier in my opening comments and I just wanted to put something out there because I am not sure we will have a hearing entirely devoted to the Great Lakes and climate change. But as I mentioned, the water in Lake Superior is lower, and there are studies out of the University of Minnesota at Duluth and other places showing that part of this, the opposite of the oceans where it is going up, is that because we have less ice because of the increasing temperatures and so the water is evaporating, and it is having an actual tremendous effect on the economy up there.

Just to give you a sense, in 2006 at just one terminal dock in Duluth it took 42 more ships to load the same amount of tonnage as it did in 2005 because of the fact that we are seeing a lowering of the water level in the Great Lakes. I always look for examples to use for some of my colleagues that are in states that are not on the coast areas, to use about why the climate change issue is affecting us just as it is affecting people in the coastal areas.

I know that this was not the focus of this hearing, but if anyone had any information to add to the information we are gathering on the Great Lakes that would be helpful. Dr. Feely?

Dr. FEELY. Yes. I just wanted to add, the same problems that we are talking about with ocean acidification should be also thought about with respect to the Great Lakes. The Great Lakes are lakes that are not as well buffered as the oceans, so the impacts could be even more severe. To my knowledge there has been very few studies of this particular problem. Historically, we have looked at acid rain in the Great Lakes regions and acid rain is very similar to this kind of problem because it involves sulfuric acid and nitric acid and those kinds of impacts are usually quite severe and short-lived over the seasonal changes due to snow melt and its impacts on rivers and lakes.

This is a different kind of problem because it is a gradual increase in CO_2 over a long period of time. So we should look at these kinds of issues with respect to the Great Lakes as soon as possible.

Senator KLOBUCHAR. Madam Chair, could I do one more question or are we running out of time?

Senator CANTWELL. No, absolutely ask additional questions. I thought perhaps, though, given your question, I think that Dr. Feely's slides are about acidification and acidification impact. Would now be a proper time to show that?

Dr. FEELY. Sure, I would love to.

Senator KLOBUCHAR. Very good. We have been waiting to see this slide.

[The PowerPoint presentation is retained in Committee files.]

Dr. FEELY. I actually prepared this slide for this presentation. What we have done with the global CO_2 surveys, we made measurements in the 1990s of the distribution of anthropogenic carbon in the ocean and we used that information to develop models of how the oceans will change over time with respect to saturation levels that the coral reef systems and the pteropods and many of these calcifying organisms are sensitive to.

Then we worked together with the modelers who had been working with global circulation models. This is a composite model output of the 13 best models throughout the world that have been used for these studies. What this map shows is the pre-industrial level of saturation state for the oceans in the surface waters. What we have plotted on here in the map in the very black dots are the present day distributions of tropical coral reefs. The magenta dots are the present day distributions of the deep water coral reefs.

What the tropical coral reefs need is a saturation state in excess of 3, a saturation state of 3 for them to survive naturally. We do not know what the saturation state requirement is for deep water corals because those studies have not been done.

So we move into the present condition in 2000 and we see that the system has changed. It is no longer optimal for calcification, but many of the regions are still safely within that saturation state of 3. We would prefer to have it at 3.5 or 4. Again, most of the tropical coral reefs are within that state. But we see we are now encroaching on that optimal saturation state.

If we go out to 2040, we see that now the coral reef systems in the Hawaiian Islands region and other locations are also very, very close to being well within this limit of 3.0 saturation, and therefore there is some concern whether they can continue to calcify by 2040.

The magenta regions here are the thermodynamic limit where dissolution begins to occur, and we can see that occurring in the southern ocean by 2040.

When we go out to 2100, what we see is that the entire world oceans are no longer within this level of 3.0, which means that the coral reef systems would not be able to continue to calcify. Again, the entire southern ocean would be a region of complete dissolution. In other words, no organism would be able to calcify. They would begin to dissolve.

Now we see in the North Pacific, high northern latitudes, also in the Atlantic particularly and presumably the Bering Sea, we have the same conditions of undersaturation in which the coral organisms and the other calcifying organisms would——

Senator CANTWELL. But Dr. Feely, on calcification, you are treating that like an indicator species? Or should we attribute other——

Dr. FEELY. Calcification is the process by which they form their shells. So the question is can they form their shells or not? What these models show is where they can form their shells and when the shells will actually begin to dissolve.

Senator CANTWELL. You are treating that as, you are treating that like any other indicator species as to the health of an environment, or are there other implications we should draw from that, I guess as you keep going through this?

Dr. FEELY. Yes. Well, for example, for coral reefs, this means whether they can continue to produce their skeletons. But for other species, this would suggest that they would no longer be able to calcify. For example, the pteropods which are the primary food source for salmon would no longer be able to form their calcium carbonate shells. So these are the regions where they would have to be—no longer can exist in those locations. So they would be removed from those locations. So the food chain would change dramatically.

Senator CANTWELL. So you are saying they are the beginning of the food chain indication?

Dr. FEELY. Right.

Senator CANTWELL. Is that what you are saying?

Dr. FEELY. That is exactly correct.

Senator CANTWELL. OK.

Dr. FEELY. So what we are seeing, this process of CO_2 enrichment really starts from the poles and moves toward the tropical regions. So the high latitude regimes, the high productivity regimes for fish and shellfish, are going to be affected first, and this is what we are seeing in these model outputs.

Senator CANTWELL. Thank you very much.

Senator Klobuchar?

Senator KLOBUCHAR. I think Dr. Hansen wanted to comment a little more.

Dr. HANSEN. I wanted to add something with regard to the Great Lakes. The Great Lakes have not only, as well as the world's oceans, have not only an issue of quantity—as you stated, the world's oceans are growing, while the lakes are shrinking—but also issues of water quality. In the Great Lakes region you have not only the issue of increased evaporation because of altered ice cover, but you also have periods of drought that have been occurring there.

Coupled with that drought are altered use of fertilizers and pesticides for agriculture and other human adaptations, if you will, to the changes that are already going on. And as part of that, I think that one of the concerns for the Great Lakes should be how is the water quality being protected under that changing climate regime and how do we rethink the way we set regulatory limits on things like contaminants, sewage outflow, in response to the fact that there is now less water in that water body that historically has been receiving those outputs.

Senator KLOBUCHAR. Thank you.

My last question was for you, Admiral Watkins. As we looked at all the enormous challenges we are facing, you had some ideas for solutions, and obviously some of it is the funding for research. But I was interested in your idea of the more integrated management of our ecosystem and if you could just spend a little time explaining that to us as we look at how we can better do things in addition to the additional funding.

Admiral WATKINS. Well, let me say first, Senator, that I do not know if you noticed, but when we put out our draft report in the spring of 2004 the biggest negative comment we had on that draft was from the Great Lakes area saying, it is oceans, coasts, and Great Lakes. We agreed and you will see it in our report. It is not only what we just heard here, but also invasive species are coming in there and destroying the fisheries.

Senator KLOBUCHAR. The Asian carp.

Admiral WATKINS. It is a huge issue. If you ask the White House, what are you doing you will hear: Look, we have established a task force, we have got a Federal to State relationship, we have got the Canada-Great Lakes Commission, it has been there for many, many years. And the answer is: Yes; what have you done? And the answer is not very much.

So it is like everything else. It is a lot of rhetoric and very little substance to the investment that we need in the Great Lakes. But it is part of the whole regime that we are talking about here. We are saying that we need to have a governance response and we need to have a science response, and both of those come into play for the Great Lakes.

On the governance side, we have mentioned to Congress in our reports we need to codify and strengthen NOAA. That should be a pigh priority of this Committee to pass a NOAA Organic act. NOAA should focus on three core functions: assessment, prediction, operation; research and education; and marine resource and area management; a realignment that would benefit the Great Lakes.

Congress should also request a National Academies study to make organizational recommendations for a national climate change response office. That could deal with the Great Lakes issue. It should also require an integrated budget in support of the national climate change response office.

This Committee, members of this Committee here and other committees, sent a letter 2 years ago to the White House saying, we want an integrated ocean policy budget submission. If you want to send them up this way, from 15 agencies, that is fine, but horizontally integrate them and get them up here, so we can tell; are you doing anything. So far we have not seen such a budget, so the answer is no, they are not doing anything. So it is all superficial stuff.

So again, the Great Lakes get affected by all that.

We say codify and strengthen the White House Committee on Ocean Policy. Could this work in the current system? Yes. All the President would have to say is: Do it, Mr. OMB, and do it, Mr. Adviser, the Policy Adviser. That happened to me when I was Secretary of Energy. I wanted to clean up the bomb factory after 40 years when the Cold War ended. It was President H.W. Bush who said: No, Mr. Secretary of Defense, I know it is coming out of your hide, but we are going to do it. We went from $800 million a year to $6 billion. Now it is $7 billion. We are turning Rocky Flats back to the State of Colorado, Fernault back to the State of Ohio.

So we can work with the current system if we want to do it. So it really starts in the White House. I think if they took the lead the Congress would respond very positively.

So then we want to codify the Committee on Ocean Policy, to prevent it from disappearing, since it currently exists under an executive order. That is how NOAA was established via an executive order, and we do not want that any more. We want Congress to codify NOAA to give them responsibility, accountability, and resources. Of the $750 million a year over JOCI recommended, about 60 percent of that would go to NOAA, to support all the projects that we have outlined in our report.

So that addresses the governance issue. On the science side, we say fund the climate-related research priorities in the administration national ocean research priorities plan. They have a plan that was released in January. Fund it. And you know, in the initial funding for the plan they allowed NASA to refuse funding to support its Earth sciences. So I do not trust implementation of that plan solely by the Administration. So Congress has to codify it and say: No, we expect it to do its job.

Fund the Integrated Earth Observing System. We have heard that here today. We have got to have a comprehensive observation system. We have got to know what is going on out there. And we can build on that. It is 50 percent completed now, but not in the ocean. There is not even close to 50 percent there. We are way down at the bottom of the heap in terms of our science, technology, data management, ability to convert data into useful product.

Senator CANTWELL. Admiral Watkins, if I could jump in here, are you suggesting that we incorporate the oceans impact when we are talking about setting a target for CO_2 emissions reduction? And if we were, how would you do that?

Admiral WATKINS. Well, the Oceans Commission was never tasked by the Congress to do that. We are on the fringes of it because we kept running into the time. But we could not address it. So we did not feel we had the mandate out of Congress to deal with greenhouse gas mitigation. Obviously, as Secretary of Energy when I was there we did. We ran some of the ocean flux studies. We ran the carbon cycle. We put a lot of emphasis in this.

I think it dissipated at that point. So I have some personal views on it, but I do not have any clues as to—you know, there has been so much talk about this, to give a specific number and set these. I am on the same wavelength as some of the witnesses this morning on doing both mitigation and adapting, and adaptation. We have not addressed the subject of adaptation at all and that is sad, because for the next two and a half decades, no matter what we do with greenhouse gas reduction, we are going to have a problem of global warming. It is there for us to deal with and we have got to manage our way through it. So we need both.

Senator CANTWELL. Well, let us turn to Dr. Feely on that so we can understand, because I think that the Fiscal Year 2008 budget would decrease about 14 percent from the 2006 level research related to acidification. Is that correct?

Dr. FEELY. Yes, Senator, that is correct.

Senator CANTWELL. And we do not have any money for adaptation?

Dr. FEELY. Well, the research that is presently being provided for directly funding ocean acidification research is about $1.6 million per year throughout all the Federal agencies. There is an additional $4 million per year that is being funded within NOAA on related activities to ocean acidification, but they are not directly funding ocean acidification research.

We draw from that additional related research to identify and proceed on ocean acidification studies. But they are not directly funded for doing ocean acidification studies.

Senator CANTWELL. You have suggested, I think, four themes. One would be—in this research realm. One would be monitoring. Another would be understanding the response of the animals to acidification, ecosystem modeling, and risk assessments.

Dr. FEELY. That is correct.

Senator CANTWELL. So do you have a sense of how much that would cost in the context of where we are today and where we need to get a clear picture of ocean health and a plan?

Dr. FEELY. Well, we have discussed this in a number of workshops that involve the scientists that are doing ocean acidification research and related activities. In those workshops, the community has indicated that a national program on the order of $30 million per year would be appropriate.

Senator CANTWELL. Dr. Hansen, did you—in best practices on adaptation, what do you think are the key things that we should be looking at?

Dr. HANSEN. Well, the first thing is that we actually need the capacity to do this type of work. We are not training people to do this work whatsoever. We are also not raising the awareness of people that it needs to be done. Many people are still trying to pretend that climate change either is not happening or someone else is taking care of it. Unfortunately, it is a reality for all of us.

So the sort of steps that I have laid out in my testimony and that my colleagues and I have been talking about is first the need to train the next generation of people who will be taking this on, as well as getting ourselves up to speed on it; developing some sort of extension agency that actually is going out, raising awareness about this issue, engaging people on what the options are, getting them to implement them, and taking the lessons back to synthesize and provide the next generation of guidance.

Then finally, we need to be incorporating climate adaptation into literally everything that is being done in national and local and international legislation, quite frankly, where we are preparing all of the projects we are working on so that they are climate-prepared, be it in coastal infrastructure, preparing it for sea level rise, be it agriculture, preparing it for periods of drought or movement of pest species, forestry, preparing for increasing fire regimes, fisheries, preparing for movement and new management strategies.

Literally every sector of our society is and will continue to be impacted by climate change for decades to come, and we are grossly underprepared for that.

Senator CANTWELL. Dr. Kruse, it seems that you are kind of on the front lines there in Alaska with the polar bears and walruses and seals being impacted by melting ice. What can managers do on these species?

Dr. KRUSE. Thank you for your question. Certainly these climate changes are out of the purview of fisheries managers, but fisheries managers need to deal with the ramifications. So one of the clearest things we can do is be more precautionary. So if there is potential for fishery interactions with either of those species directly or indirectly through their prey base, I think we have to be more precautionary.

As I indicated briefly in my oral remarks and more fully in my written remarks, the North Pacific Fishery Management Council is looking at establishing perhaps an Arctic Fishery Management Plan that would basically set those areas off limits, particularly with an eye toward the loss of sea ice. The loss of sea ice reduces habitats for the ice seals and polar bears. Associated with the loss of sea ice, we may see a switch from that system, which is a more benthic system that support prey of birds like the spectacled eiders and walruses to a pelagic system. Realizing that these changes are happening, maybe it is best to not allow any fishing there.

At their next meeting in June 2007, the North Pacific Fishery Management Council is looking at defining what we call essential fish habitat. They will consider basically freezing the northern boundary of the current areas that are being fished in the Bering Sea, even realizing that fish may move north, into previously unfished areas wtih increasing temperature. The problem is that we simply do not have data nor surveys up there, so we do not know what is there, and we realize that these northern ecosystems can be very fragile with respect to species, such as some of the seabirds, the marine mammals. Certainly the coastal residents of those northern areas make use of those marine resources and really depend on them for their survival.

So being more precautionary I guess is the short answer.

Senator CANTWELL. Dr. Conover, do we have to take this into consideration in implementing the Magnuson-Stevens Act?

Dr. CONOVER. Yes. I think one of the most important shifts that we are seeing in how we manage marine resources is to take a more ecosystem-based approach. In an ecosystem-based approach, then the impacts of climate change can be folded into the decisions we make about how heavily we can harvest various species or whether we need to back off.

A lot of the things we see happening in my region of the world go beyond just the impacts of harvesting and include diseases, the impacts of water quality, hypoxia, and all those end up having an impact on the abundance of the species we are trying to protect. So using an ecosystem approach, which really we have only begun to do recently, lends itself to thinking longer term rather than year to year, and including expectations of climate change in that approach.

Senator CANTWELL. Admiral Watkins, I am going to give you the last word, with the emphasis on "last." But if you could briefly, what do you think that we need to change from a policy perspective? Why from a political sense are we not getting this done? What are the road blocks and what do you suggest that we do to take the information we have had to date at this hearing and integrate that into policy action?

Admiral WATKINS. Well, you used the term here "ecosystem-based management." That is not a trivial issue. Eyes roll back when you tell that to the public, but in Washington we know what it means. It means major reorganization of how we do business here. Horizontal integration across Federal agencies, up here on the Hill and so forth becomes very important when you get into climate change practices. We cannot separate these things. So we have to kind of back away from the old way of doing business, take advantage of the information technology world we live in, bring business and industry into the game to help us build these architectural systems that we want to observe, get the database straightened out, be able to convert that data to useful products at the local, county, State levels.

We should be able to do all this, but the current governance regime is a big hindrance right now. There is no process to integrate activities across the Federal Government. That is what we have got to deal with. That is why we put so much emphasis on governance. It is not that governance will answer everything. Obviously, you have to have a budget and you have to have educational programs. You have to have a lot of things. But if we are going to spend the money right, we better do it right, and we better do it the way nature does it. We fouled it up by managing it piecemeal, vertically. Nature beautifully integrates horizontally and tells us what the problem is. And we need to listen to that, and then we need to manage within the natural process, and we are not doing that today at all.

So that is why I put so much emphasis on governance. And obviously the science is the other critical component. We have not put adequate emphasis on it. When the President announced his new American Competitiveness Initiative two years ago in the State of the Union Address, oceans were not in the game. They are not even considered in this.

So we have not put emphasis on science, in particular, ocean science. The Office of Science and Technology Policy also used to be the Science Adviser to the President. He is no longer the Science Adviser to the President. It was removed. Is science important to the administration or not? I do not think so, not sufficiently important, particularly when you get into this area of climate change.

So we have got a major job to do in the way we look at this, and that is why, because the Senate has been so receptive to our work over the last few years, we are kind of counting on the Senate to take the lead. We tried the White House and we do not get enough response. I do not know that Jim Connaughton is not doing a decent job, but he is not given the time of day and the strength to put the money into the budget process, to give you a budget up here that is other than what we have always done.

I will say the administration this year in the 2008 budget finally put in a figure that was comparable to the 2007 appropriated. They have never done that before. So is that a plus? Well, yes, I guess so, but not a big plus.

Senator CANTWELL. We will stop on that note.

Admiral WATKINS. Anyway——

Senator CANTWELL. Because we all do want to work together, and I appreciate your point. You had the scientists nodding at the other end of the table about how we should look more at the environment and its response from a systematic perspective.

I will point out that I think the Pacific Northwest, particularly Washington State, has done fabulous work on two areas, timberfish and wildlife, which is industry working together with environmentalists. In fact, those ecosystem plans, if they are ever challenged, you get the industry officials as aggressively responding as you do the environmentalists. So I think it has been a good measure. I think Bill Ruckelshaus has done fabulous ecosystem work as it relates to salmon recovery in the Northwest, again working with a whole cadre of local governments, Native Americans, fishermen, industry officials across the board. So we may be a little bit more of a forerunner on that.

And as I mentioned, the Pacific Northwest Fishery Council I think has been a forerunner in implementing environmental impacts and management into their fisheries policy ahead of the rest of the Nation. So we obviously do care greatly about our environment in the Northwest, including our ocean.

So I want to thank all the panelists for a very detailed presentation about the challenges that we face with our oceans policy. Admiral Watkins, I hope that my colleagues will review all of this. Obviously, we are going to leave the record open for additional questions. If you could help us and comply by answering that in a quick fashion, we will leave the record open for a few weeks. But I hope my colleagues will take this hearing and take the testimony and take up the baton that you are passing to us to act and to consolidate this as part of our response to healthy oceans.

So thank you all very much. We are adjourned.

[Whereupon, at 11:52 a.m., the hearing was adjourned.]

A P P E N D I X

PREPARED STATEMENT OF HON. DANIEL K. INOUYE, U.S. SENATOR FROM HAWAII

Coral reefs have been called "the rainforests of the sea." In addition to their great beauty, they offer critical habitat to a variety of marine organisms. Coral reefs cover less than 1 percent of the Earth's surface, but they provide resources and services worth approximately $1.4 billion annually to the U.S. economy. In the State of Hawaii, the economic value of coral reefs is estimated at more than $360 million annually.

These diverse coral habitats have survived for millions of years, recovering from natural disturbances. However, the reefs are under threat from rising ocean temperatures and increasing ocean acidity. Scientists are observing coral bleaching that is more widespread and more severe, in some cases, severe enough to kill the corals.

I am pleased the Administration is proposing legislation to reauthorize and strengthen the Coral Reef Conservation Act of 2000, legislation that I introduced in 1999 to establish the Coral Reef Conservation Program within the National Oceanic and Atmospheric Administration.

However, this legislation will not be effective in protecting coral reefs if we do nothing to reduce carbon emissions.

Coral reefs are just one of the kinds of living marine resources that are impacted by climate change. Scientific research has confirmed that emissions of greenhouse gases contribute to climate change and that such emissions are causing our oceans to become warmer and more acidic. These effects are harming our living marine resources. The science is also clear that these impacts will grow worse as long as we continue to do nothing to reduce greenhouse gas emissions.

Therefore, I hope that our distinguished panel members will be able not only to help us understand these impacts, but also to suggest a way forward.

PREPARED STATEMENT OF HON. FRANK R. LAUTENBERG,
U.S. SENATOR FROM NEW JERSEY

Madam Chairman, thank you for holding today's hearing.

Despite the Bush Administration's ongoing efforts to censor and suppress science, there is no doubt that man-made global warming is real, and it threatens the health of our planet, including our oceans.

The increase in carbon dioxide causes global warming and ocean acidification.

NOAA researchers predict that oceans will continue to acidify to "an extent and at rates that have not occurred for tens of millions of years." Ocean acidification threatens our marine ecosystems. As the chemistry of our ocean changes, some marine life may not be able to survive.

Acidic water damages our corals, for example, which provide vital habitat to many marine species, and plankton, the foundation of the marine food chain.

In addition, the rise in ocean temperature has caused some fish to move to colder waters, posing challenges to our commercial and recreational fisheries.

The combined effects of global warming and ocean acidification cannot be ignored. The potential environmental and economic cost to New Jersey—and coastal states across the country—is too great.

I am concerned that the Administration is not taking the issue of ocean acidification seriously enough. In the Magnuson-Stevens bill we passed last year, Congress directed the National Research Council to report on ocean acidification and its impact on the United States. I have requested funding for this authorized study as a member of the Appropriations Committee, and I will work with my colleagues to see that the effects of ocean acidification are made a priority for this Administration.

Thank you again Madam Chairman for beginning our work on this important issue.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. DANIEL K. INOUYE TO SCOTT C. DONEY, PH.D.

Question 1. Coral reefs are not just critical habitat for fish. In my state of Hawaii, they are also an economic engine supporting both fishing and tourism. Is ocean acidification or the increase in sea temperature the more pressing issue for protecting and preserving Hawaii's coral reefs and other marine resources and why?

Answer. Surface ocean warming and acidification are two sides of the same coin because their root cause is the same, namely the human-driven rise in atmospheric carbon dioxide. Therefore we need to address both issues simultaneously. Warming has already been linked to coral bleaching events. Acidification has been shown to limit coral growth in the laboratory, and more work is needed to assess the impacts on whole ecosystems. One concern is that the combined effect of temperature and warming may be much more harmful on coral reefs than either factor in isolation. Thus it is difficult to separate temperature and acidification effects and to assign one factor or the other as the most pressing issue; they are both important.

Question 2. How can we incorporate actions to address these issues into an overall management strategy for protecting Hawaii's corals and other marine resources?

Answer. Climate warming and acidification are global processes that are not easy to reverse at the local or state level (see below). Management strategies, however, can be developed to minimize their impacts on coral reefs and fisheries. The first step is to reduce the negative effects of other factors that are more amenable to local control. These include things like pollution, land runoff of excess nutrients, overfishing, and habitat destruction. The second step is to create more adaptive, forward-looking management strategies that explicitly include climate warming and acidification in their design. For example, the catch limits for many fisheries are set based on historical levels of fish stocks. But the future ocean will not look like the past. Numerical climate models will provide some guidance for helping resource managers, but at present there remain relatively large uncertainties in our forecasts of the magnitude in climate change on regional scales and resulting biological responses. Following a precautionary principle, one strategy would be to lower present catch limits to provide an additional safety factor for unforeseen climate impacts and to closely monitor resource levels to maintain sustainability. Climate change and ocean acidification also need to be factored into the design of other management tools such as marine reserves or marine protected areas. For example, as species distributions shift with climate, will the size of a protected area be sufficient and will it still protect the target species of interest.

Question 3. Dr. Doney, could you tell me what adaptation and mitigation steps you think the United States needs to take to address the threats that climate change and ocean acidification pose to our ocean resources?

Answer. Increasing surface water temperatures and ocean acidification are driven by the human emissions to the atmosphere of greenhouse gases like carbon dioxide. The atmosphere mixes on time-scales of months to a few years, and the climate impact of carbon dioxide emissions is global rather than local. Thus ocean warming and acidification require global solutions to limit the rise in atmospheric carbon dioxide. The most direct mitigation steps would be to reduce the amount of carbon dioxide released to the atmosphere. Reducing emissions can occur through shifts to non-fossil fuel energy sources, increases in energy efficiency, and deliberate actions to sequester carbon rather releasing it to the atmosphere. One of the more promising sequestration approaches appears to be storage of carbon dioxide in geological reservoirs, such as old natural gas and oil fields. There are also proposals to manipulate land and ocean ecosystems to remove some of the excess carbon dioxide in the atmosphere and increasing carbon storage plants, soils and the deep ocean. Adaptation strategies are discussed in the answer above.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. MARIA CANTWELL TO SCOTT C. DONEY, PH.D.

Question 1. The most rigorous mitigation goal in the recent summary report by the Intergovernmental Panel on Climate Change is to stabilize atmospheric greenhouse gas levels between 445 and 710 parts per million by 2030. But given that the current concentrations of atmospheric carbon are estimated at 379 parts per million, shouldn't this target be set at a much lower level if we are to effectively address climate change? What is the expected temperature increase of this range?

Answer. The IPCC stabilization scenarios from the 4th IPCC Assessment report are discussed in some detail in the Technical Summary for Working Group III (Mitigation). I think the specific values of 445 to 710 parts per million are drawn from

Table TS. 2 (page 21 and 22 of the draft Technical Summary); the same table is given as Table SPM.5 on page 23 of the Summary for Policymakers. This table is somewhat confusing as it lists two columns of carbon dioxide (CO_2) levels, one an actual CO_2 level and the other the "equivalent" CO_2 level, that is the amount of CO_2 that would be needed to match the total radiative warming of excess CO_2 plus the other human driven greenhouse gases (methane, nitrous oxide, chlorofluorocarbons, etc.).

(numbers from Table TS. 2; IPCC 4th Assessment, Technical Summary, Working Group III)

Category	CO_2 (ppm)	Equivalent CO_2 (ppm)	Equilibrium temperature change (deg. C)
I	350–400	445–490	2.0–2.4
II	400–440	490–535	2.4–2.8
III	440–485	535–590	2.8–3.2
IV	485–570	590–710	3.2–4.0
V	570–660	710–855	4.0–4.9
VI	660–790	855–1,130	4.9–6.1

The most extreme stabilization scenario is for stabilizing roughly present day conditions (CO_2 of 350–400 ppm; equivalent CO_2 of 445–490 ppm) by 2100. This is a very rigorous goal and would require reductions of all greenhouse gas emissions by 2015 and net removal of CO_2 by some means (*e.g.,* growing biomass) toward the end of the century. A series of stabilization scenarios are then presented that allow for higher atmospheric CO_2 (and equivalent CO_2 because of the other greenhouse gases).

Two different temperatures are often reported for stabilization scenarios, the transient temperature at some point in time along a pathway and the equilibrium temperature. Even once atmospheric greenhouse gas levels are stabilized, the planet will continue to warm for an extended period of time. The temperature differences given above are for the equilibrium global mean temperature. Equilibrium temperature changes relative to pre-industrial levels are estimated by IPCC to range from 2.0–2.4 deg. C for the most aggressive stabilization scenario (marked I in the table above). The temperature increases grow as higher stabilization CO_2 levels are allowed, reaching 4.9–6.1 deg. C for the most lenient case examined. Even these values are considerably less than some business as usual scenarios considered in IPCC.

Question 1a. What would be the impacts on our ocean resources if we were to reach these emissions levels?

Answer. Even if we were to eliminate all greenhouse gas emissions to the atmosphere, the ocean and the planet would experience some additional amount of warming and acidification beyond current levels (global mean temperature increase of 0.76 ± 0.19 deg. C and surface pH drop of -0.1 units) because of the inertia in the climate system. Even the most aggressive IPCC stabilization scenarios lead to further warming and acidification beyond what we have already experienced (see above). Broadly speaking, there is a strong consensus that reducing the total amount of climate change will lessen the impacts of climate change and acidification on ocean resources. For some specific ecosystems we can make estimates of the trends such as reductions of some species and increases in others, poleward shifts in the ranges of warm-water species, further degradation of coral reef systems, etc. Making more detailed, quantitative forecasts for biological systems comparing the impacts for one stabilization scenario versus another is more difficult at present because of uncertainties in our scientific understanding. Biological systems are not linear, and it is likely that at least for some regions with larger climate change and acidification ecosystems will reach thresholds beyond which there will be significant and dramatic changes in ocean resources. Equally important is the rate at which the changes are occurring. Faster rates of climate change and acidification give species less time to adapt or to migrate to different regions where conditions may be more favorable. Faster rates of change also introduce additional social and economic problems, particularly when significant changes happen over a time-scale short relative to the lifetime of infrastructure used for a particular ocean resource (*e.g.,* fishing fleets).

Question 2. How can we improve our ocean and Earth observation programs to ensure understanding of the impacts of global climate change and ocean acidification on the marine environment?

Answer. The U.S. and other countries are putting in place elements that will contribute to a global ocean observing system, but there remain a number of gaps in such a system. First, much of the current in-water observing network measures physical properties of the ocean. Documenting ocean physical changes is key, as physical changes drive biological changes. But there needs to be a corresponding rapid expansion of in-water chemical and biological properties. In some cases, we need to invest in the development and testing of new sensors to routinely measure seawater chemistry and biology. For example, there is an international network that uses volunteer observing ships (cargo freighters, research vessels) and some moorings to measure surface ocean carbon dioxide levels. Given concerns with ocean acidification, that network needs to be expanded in scale (*e.g.,* by using autonomous drifters and profiling floats) and in scope by including pH measurements.

Second, the U.S. needs to maintain and extend the capability to monitor ocean trends from space using satellite-based remote sensing. For ocean biology, sensors measuring ocean color, a proxy for surface water phytoplankton chlorophyll, have been invaluable in understanding biological spatial patterns and dynamics on timescales from seasonal to multi-year. We will soon have 10 years of data from the NASA and GEOEYE SeaWiFS sensor. The future of U.S. ocean color remote sensing and other routine satellite ocean measurements is somewhat in doubt with the transition of many measurements from NASA research mode to an operational mode under NPOESS by NOAA and DOD. In particular, the requirements for long-term climate data records (*e.g.,* consistency across time and across satellite platforms) can be more demanding than those for operational needs, and it is not clear that the appropriate investments are being made within NPOESS.

Question 3. What are the potential impacts of some of the currently proposed climate change mitigation strategies on the marine environment—such as iron stimulated plankton blooms or injection of CO_2 into sea sediments?

Answer. Ocean iron fertilization has been proposed as a carbon mitigation strategy because phytoplankton growth is limited by the availability of the trace nutrient iron in some oceanic regions. As indicated by the results from about a dozen deliberate experiments, adding iron causes the plant-like phytoplankton to bloom, drawing down seawater carbon dioxide levels. What is not clear, however, is the long-term fate of the newly formed organic matter. If this material is converted back to carbon dioxide in the surface ocean by respiration, the net effect on ocean carbon storage will be small. If on the other hand some of the carbon is transported to the deep ocean, iron fertilization could act to sequester carbon and lower atmospheric carbon dioxide levels.

Several concerns have been raised about the potential impacts of iron fertilization:

1. To be effective, iron fertilization must alter ecosystem dynamics, and the environmental consequences on other parts of the food web are not well understood. For example, how will iron fertilization effect fisheries? Will it increase the likelihood of harmful algal blooms? Because of ocean circulation, the environmental impacts of iron fertilization may arise either locally near the fertilizationsite or non-locally downstream.

2. Iron fertilization may stimulate the production and release to the atmosphere of other climate greenhouse such as nitrous oxide and methane. Since these gases are much more potent greenhouse gases on a per molecule basis, the release of these gases may greatly decrease the effectiveness of iron fertilization as a mitigation approach.

3. Increased carbon export to mid and deep-ocean could decrease subsurface oxygen levels, increasing the size of oxygen minimum zones.

Two other proposed carbon mitigation strategies include direct injection of carbon dioxide into the deep ocean water column or into deep-sea sediments. Deep-sea sediment injection would have local impacts on benthic (bottom) and water-column ecosystems because of the infrastructure required for injection. If the leakage of carbon dioxide into the overlying seawater can be minimized, the environmental consequences on the ocean water column will be relatively small. Direct injection of carbon dioxide into the ocean deep waters will result in a lowering of seawater pH and ocean acidification. Locally around the injection site the resulting acidification will be much larger than that observed in the upper ocean. Extrapolating from studies of surface species, one should expect significant negative impacts on calcifying species (deep-sea corals, mollusks). Some studies suggest only minimal acute (short-term) effects on fish; less clear are the longer-term, chronic effects. There will also be local dissolution of carbonate bottom sediments. Some injection schemes involve pumping down liquid carbon dioxide, which is heavier than seawater and will form concentrated pools along the ocean bottom. Benthic life will be destroyed underneath the liquid carbon dioxide pools, but the effected area would be considerably smaller than if the carbon dioxide were dispersed in the seawater. The environmental impacts will depend upon the extent to which the liquid carbon dioxide mixes into the overlying seawater.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. FRANK R. LAUTENBERG TO SCOTT C. DONEY, PH.D.

Question 1. According to NOAA, about 4,000 species of fish, including approximately half of all federally-managed fisheries, depend on coral reefs and related habitats for a portion of their life cycles, and the National Marine Fisheries Service estimates that the value of U.S. fisheries from coral reefs exceeds $100 million. Will corals and plankton be able to survive or adapt to more acidic waters in our oceans?

Answer. Our current information on the impacts of ocean acidification is based almost entirely on short-term (days to months) studies of shell forming plants and animals to large increases in carbon dioxide. Higher CO_2 will affect other organisms (non-shell forming plankton, juvenile fish, etc.) but there is considerably less data on non-calcareous (shell forming) organisms. Most of the experiments to date have been conducted either in the laboratory or in small controlled conditions (for example, outdoor seawater tanks or floating tethered bags filled with seawater). The observed effects of acidification include decreased calcification rates (slower shell-formation), reduced growth rates, and in some cases reduced reproduction rates. Extrapolating from those results to the ocean, where the rise in carbon dioxide will be more gradual, involves considerable uncertainties.

The ability of calcifying organisms to survive or adapt to high CO_2 conditions likely varies from group to group. Some types of organisms, such as phytoplanktonic coccolithophores, have species or ecotypes that can survive without a calcareous shell, and under high CO_2 conditions the population may shift toward the non-calcareous variants. The shells of other groups of calcareous organisms such as pteropods (planktonic marine mollusks) and most corals appear to be integral to their life history. Most organisms experience variations in seawater chemistry naturally due to seasonal cycles and year to year variability. It is not well known the degree to which organisms may possess mechanisms to adapt to small levels of acidification or the extent to which those mechanisms would be effective (even over decadal time-scales) against the significant levels of acidification projected by the middle to end of this century. A recent study (Fine and Tcernov, *Science,* Vol. 315, page 1811, 2007) showed that a Scleractinian coral species could grow as individual polyps without shells at high CO_2 levels; while this demonstrates survival to acidification, the ecological impact of these naked polyps would be dramatic as they no longer would contribute to reef formation.

Question 1a. If they cannot, what are the implications for other marine species and the ocean's food chain?

Answer. Calcareous organisms are important components of ocean food webs, and the reductions in calcareous organisms due to acidification likely will have broad ecological effects. The gradual build-up of warm-water coral skeletons produces reefs that provide habitat for some of the richest marine ecosystems on the planet. The size of reefs reflect a dynamic balance between calcium carbonate production that adds to the reef and loss processes (storms, human reef destruction, etc.) High CO_2 conditions will likely shift the balance and may cause a reduction in the size of reefs. Similar decreasing trends for cold-water corals would result in habitat loss on the continental shelf and slope in temperate to polar latitudes. Planktonic calcareous organisms play important roles as prey for larger species. For example pteropods (small planktonic snails), which are abundant in the North Pacific and Southern Ocean, are eaten by fish (*e.g.,* salmon) and baleen whales. At present it is not clear how the impacts of acidification will filter through the rest of the ecosystem and whether and how predator species will adjust to the loss calcareous prey.

Question 1b. Species have migrated in response to ocean temperature changes. Will marine organisms migrate to avoid acidification?

Answer. The ranges for calcifying species are expected to shift in response to acidification. Most experiments show that organisms are sensitive to the carbonate ion concentration and the saturation state for carbonate minerals, both of which decrease as pH declines. Seawater carbonate chemistry varies with temperature, and under present conditions saturation decreases as one moves poleward. Under a high CO_2 world, species ranges therefore would have to shift equatorward to maintain the same saturation state. In contrast, global warming will drive species ranges poleward. One concern is that the opposing forces of warming and acidification will eliminate the combined temperature and saturation state niches to which some organisms are adapted.

Question 2. There have been ocean acidification events in the past that have resulted in the disappearance of marine organisms, including corals. What does the fossil record reveal about the adaptation of marine organisms to changes in ocean acidification?

Answer. Several different lines of geological evidence suggest that ocean seawater carbonate chemistry has varied in the past in response to alterations in atmospheric carbon dioxide levels and variations in the weathering rates on land and deposition rates of carbonate minerals in the ocean. Several processes buffer (damp) ocean pH variations on the gradual time-scales of several thousand to several hundreds of thousands of years that characterize many geological changes. The current rate of ocean acidification is many times that of prehistoric rates and because of the slow time-scales of ocean buffering the pH changes over the next several centuries may be much larger than those experienced throughout most of the geological record. Ocean pH levels have already dropped by 0.1 since the preindustrial period, comparable to the pH change thought to have occurred between glacial and interglacial cycles, and an additional pH decrease of $0.14-0.35$ may occur by the end of this century.

Past analogues to present acidification may have occurred in several catastrophic events in the geological record where it appears that large amounts of carbon dioxide were released rapidly into the atmosphere-ocean system, resulting in ocean acidification and dramatic reductions in marine carbonate burial. The more extreme episodes are associated with minor to major biological extinction events, which because of the way the geological time-scale was originally developed using paleofossils, often fall at the boundaries of geological periods. A number of hypotheses have been proposed (*e.g.,* isolated refuges) for why some species (or groups of species) survive these acidification events and others do not, but the exact reasons are not well understood.

Question 2a. How long did it take for corals and other marine organisms to recover from the acidification events in the past?

Answer. The recovery time-scales to past geological events most likely were determined by both biology and geochemistry. One of the best documented events occurred during the Paleocene-Eocene thermal maximum (PETM) about 55 million years ago. The PETM is marked by rapid increases in temperature and alterations in the ocean carbonate system over about 1,000 to 10,000 years followed by a more gradual relaxation over several hundred thousand years. A large acidification event throws off the balance of alkalinity input and removal from the ocean, and the hundred thousand year relaxation timescale can be explained as the amount of time required for the ocean alkalinity cycle to come back into balance through carbonate and silicate weathering on land. There is only a limited fossil record to reconstruct what happened to calcifying organisms during the PETM because carbonate sediments are not buried under acidic conditions. Following the PETM, there was a biological radiation of calcifying organisms.

Question 3. Dr. Feely indicates in his statement that "the atmospheric concentration of carbon dioxide is now higher than experienced on Earth for at least 800,000 years and is expected to continue to rise*the oceans are absorbing increasing amounts of carbon dioxide . . . and the chemical changes in seawater resulting from the absorption of carbon dioxide are lowering seawater pH." Have scientists determined a dangerous level of pH that we need to avoid?

Answer. A report from the German Advisory Council on Global Change (WBGU) recommends that the surface seawater pH decrease from preindustrial conditions be limited to 0.2 pH units or less on scales of either individual ocean basins or the global average (Schubert *et al.,* 2006). Estimates are that surface pH has already decreased by 0.1 since the preindustrial (30 percent drop in H^+ concentration); a pH drop of 0.2 would result in a 60 percent decline in H^+ concentration. Lower pH increases the solubility of calcium carbonate minerals (aragonite and calcite) making it more difficult for marine organisms to make shells, and the rationale used by Schubert *et al.,* 2006 is that we should avoid a pH drop large enough to drive aragonite understaturated in surface water (aragonite is the more soluble mineral form used by corals and pteropods). The 0.2 pH criteria is set by the surface waters of the Southern Ocean, which are already close to undersaturation.

R. Schubert R., H.-J. Schellnhuber, N. Buchmann, A. Epiney, R. GrieBhammer, M. Kulessa, D. Messner, S. Rahmstorf, J. Schmid, 2006: The Future Oceans—Warming up, Rising High, Turning Sour, Special Report from German Advisory Council on Global Change (WBGU), ISBN 3–936191–14–X, *http://www.wbgu.de* 110 pp.

Question 3a. At the current rate of carbon dioxide emissions, how long will it take for the oceans to reach a dangerous level of pH?

Question 3b. Have scientists determined at what level of carbon dioxide concentrations we need to maintain in order to avoid this dangerous level of pH?

Answer. Few model simulations have been run with constant present-day emissions so question b) is a little difficult to answer directly. Rather most model simulations have been conducted either with either IPCC scenarios of carbon dioxide emissions or atmospheric carbon dioxide stabilization trajectories. Orr *et al.,* 2005 report that the 0.2 pH criteria would be reached and wide-spread aragonite undersaturation would occur in the Southern Ocean with IPCC business as usual emission scenarios between 2060–2075. Based on scenarios to stabilize atmospheric carbon dioxide by 2100, Calderia and Wickett found that a carbon dioxide stabilization target of 540 ppm would lead to a global surface pH drop of 0.23, exceeding the 0.2 criteria. A carbon dioxide target of 450 ppm would lead to a global drop of 0.17 pH units.

Caldeira, K. and Wickett, M.E. Anthropogenic carbon and ocean pH. *Nature* 425, 365 (2003).

Orr, J.C., V.J. Fabry, O. Aumont, L. Bopp, S.C. Doney, R.A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joos, R.M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray, A. Mouchet, R.G. Najjar, G.-K. Plattner, K.B. Rodgers, C.L. Sabine, J.L. Sarmiento, R. Schlitzer, R.D. Slater, I.J. Totterdell, M.-F. Weirig, Y. Yamanaka, and A. Yool, 2005: Anthropogenic ocean acidification over the twenty-first century and its impact on marine calcifying organisms, *Nature,* 437, 681–686, doi: 10.1038/nature04095.

Question 4. In light of the latest findings published last month in the journal *Science* in which the biological consumption and remineralization of carbon in the "twilight zone"—a zone in the ocean where some sunlight reaches but not enough for photosynthesis to occur at ocean depths between about 660–3300 feet—actually reduces the efficiency of sequestration (Buesseler, *et al.,* Science 316, 567, 2007). What does this mean for the future of carbon sequestration in our ocean if carbon is recycled back into the surface ocean and atmosphere faster than originally thought?

Answer. Ocean scientists have known for several decades that much of the particulate organic matter that sinks out of the surface layer is consumed in the mesopelagic (300–3,300 feet depth in the ocean). One metric used to evaluate this consumption is the respiration or remineralization length-scale, a measure of how vary down the water column an average particle sinks before it is consumed and the organic carbon turned back into dissolved inorganic carbon. The Buesseler *et al.,* study in *Science* magazine examined two regions, a low productivity region off of Hawaii and a higher productivity region off Japan. They deployed a new instrument (a floating sediment trap) that should reduces biases in estimates of sinking particle flux. The major new contribution of the paper was to better elucidate that the length-scale for organic carbon differs from region to region. The length-scale near Hawaii was quite short (most of the sinking material was consumed in the upper water-column, while the length-scale off Japan was longer (a larger fraction of the material sank deeper in the water column).

So far the experiment has been conducted at two sites and for relatively short periods of time (a few weeks). The findings do not necessarily imply that organic carbon is recycled shallower in the water column than was previously thought as the results from the two sites bracket the standard length-scale estimate derived from previous studies. These results do have implications for ocean biological carbon sequestration strategies in that in order to compute the effectiveness of a fertilization experiment, one likely needs to better understand both the surface water and subsurface ecosystems.

Question 4a. Do scientists know how much carbon sequestered to the deep ocean is being overestimated?

Answer. The Buesseler *et al.,* results do not change global average estimates of the carbon consumption rate with depth, which have been computed on large-scales (entire ocean basins) by geochemical techniques; the findings do suggest that there may be more spatial and temporal variability in the effectiveness of consumption.

Question 4b. How has this changed what scientists think about how long carbon dioxide will be naturally sequestered and how long it will take material to resurface from the twilight zone?

Answer. More field data from a diverse set of locations (and over the full seasonal cycle) will need to be collected before this question can be addressed with any confidence. Currently the results bracket prior estimates and thus there is no immediate reason to think that our present understanding of the ocean carbon system is too greatly wrong. The Buesseler data does suggest that there is great spatial and temporal heterogeneity in remineralization length-scales. Such data may also help us better characterize the underlying mechanisms driving subsurface organic matter consumption, and important factor if we are to understand how the ocean carbon system may change with evolving climate.

Question 5. It is essential to start a global research and monitoring program for ocean acidification. We should be utilizing the observing systems already in place including the undersea research program. What are your recommendations for utilizing the current infrastructure of ocean observing systems and satellites to monitor ocean acidification?

Answer. The current ocean observing system has only limited capabilities to monitor ocean acidification directly but can be enhanced with targeted investments. At present there is a large in-water observing system to measure ocean physical variables. For example, the Argo global array of profiling floats of greater than 2,800 instruments now routinely measures temperature and salinity of the upper 1,000 meters (3,300 feet) of the ocean. There is an international network that uses volunteer observing ships (cargo freighters, research vessels) and some moorings to measure surface ocean carbon dioxide levels. But the spatial and temporal coverage is much more restricted than the physical observing network, any many cases pH is not measured directly, and the measurements are typically limited to the upper few meters of the water column. The U.S. and international CLIVAR CO_2 and Repeat Hydrography Program surveys subsurface pH and ocean carbonate variables but on only a limited number of transects and on a time-scale of one occupation of each transect approximately every 10 years. Even larger gaps exist for monitoring pH in coastal waters, where the requirements for high density measurements are great because there are larger variations in space and time. There are pilot efforts underway within NOAA Coral Reef Watch program to instrument several coral reefs for routine that would serve as a model for other regions. Given concerns with ocean acidification, the ocean network of chemical and biological measurements needs to be expanded in scale (*e.g.,* by using autonomous drifters and profiling floats) and in scope by including pH measurements and other relevant variables related to biological responses to acidification (*e.g.,* calcification rates; particulate calcium carbonate concentrations, etc.). To do this, we need to invest now in the development and testing of new sensors to routinely measure seawater chemistry and biology on autonomous platforms.

Satellite remote sensing cannot measure ocean pH directly but does provide a host of valuable information for assessing ocean acidification and its biological impacts that complements the information available from in-water sensors. Satellite sensors can be used to locate and access the size of coral reefs. Blooms of planktonic coccolithophores (a phytoplankton group with calcium carbonate shells) can also be measured from space under some conditions. Satellites provide a regional context for in-water measurements because satellites often measure ocean properties over a wider window in space and time. Data analysis methods are also being developed for estimating surface water chemistry based on empirical relationships with physical and biological variables that can be measured from space (*e.g.,* temperature, chlorophyll) or estimated from ocean numerical models. The U.S. needs to maintain and extend the capability to monitor ocean trends from space using satellite-based remote sensing. For ocean biology, sensors measuring ocean color have been used to map the occurance and distribution of coccolithophore blooms from space. We will soon have 10 years of data from the NASA and GEOEYE SeaWiFS sensor. The future of U.S. ocean color remote sensing and other routine satellite ocean measurements is somewhat in doubt with the transition of many measurements from NASA research mode to an operational mode under NPOESS by NOAA and DOD. In particular, the requirements for long-term climate data records (*e.g.,* consistency across time and across satellite platforms) can be more demanding than those for operational needs, and it is not clear that the appropriate investments are being made within NPOESS. We also need to extend the capabilities of ocean remote sensing with new sensors focused on detecting changes in the ecological community (which species are present) and plankton physiology and targeting coastal and coral reef environments, which require high spatial resolution.

Question 5a. What information can be gained from monitoring natural variations over a long time period of time and in several different oceanic regions?

Answer. Ocean pH and related environmental conditions vary naturally in time (event scales such as storms, seasons, year to year variability) and in space (because of changes in temperature, upwelling of subsurface carbon rich water, and biological photosynthesis and carbon drawdown). A better understanding of the magnitude of those changes and the resulting biological responses is critical to unraveling the mechanisms by which acidification impacts ocean ecosystems. Consistent long term records of pH trends and biological responses (*e.g.,* calcification rates) would provide data to evaluate and test the climate models used to make future forecasts. More robust models would provide increased confidence to the decisionmakers and stakeholders using these forecasts. Better monitoring also would allow scientists to identify the environmental conditions under which calcifying organisms grow today and the extent to which present acidification and natural variations are already impacting calcifying organisms and whole ecosystems. Together with targeted laboratory experiments and field process studies, a monitoring network will help elucidate the ability of organisms to adapt to acidification and the changes that will occur to other parts of the ocean food web if calcifying organisms are harmed by acidification.

Question 6. This year I requested funding through the Appropriations Subcommittee on Commerce, Justice, Science to fund the National Research Council report on ocean acidification mandated by Magnuson-Stevens Fishery Conservation and Management Reauthorization Act. Has NOAA yet identified the compelling research needs for this study?

Answer. I am not aware that NOAA has finalized the scope of the proposed National Research Council report on ocean acidification, and if they have done so the research needs have not been made widely known to the public.

Question 6a. If so, what are the research needs for this report?

Answer. One concern is that if not properly framed the NOAA sponsored NRC report could be too narrowly focused solely on the needs and mission of a single agency (NOAA) and neglect the opportunities offered by an integrated, multi-agency strategy for ocean acidification. The U.S. scientific community has devoted considerable thought and effort into defining the most compelling and urgent research needs with regards to ocean acidification. These research needs are well articulated in a recent report from a workshop sponsored by the NSF, NOAA, and USGS (Kleypas *et al.,* 2006). The recommendations of this report on the major scientific issues that should be pursued over the next 5–10 years include:

- "Determine the calcification response to elevated CO_2 in benthic calcifiers such as corals (including cold-water corals), coralline algae, foraminifera, molluscs, and echinoderms; and in planktonic calcifiers such as coccolithophores, foraminifera, and shelled pteropods;
- Discriminate the various mechanisms of calcification within calcifying groups, through physiological experiments, to better understand the cross-taxa range of responses to changing seawater chemistry;
- Determine the interactive effects of multiple variables that affect calcification and dissolution in organisms (saturation state, light, temperature, nutrients) through continued experimental studies on an expanded suite of calcifying groups;
- Establish clear links between laboratory experiments and the natural environment, by combining laboratory experiments with field studies;
- Characterize the diurnal and seasonal cycles of the carbonate system on coral reefs, including commitment to long-term monitoring of the system response to continued increases in CO_2;
- In concert with above, monitor *in situ* calcification and dissolution in planktonic and benthic organisms, with better characterization of the key environmental controls on calcification;
- Incorporate ecological questions into observations and experiments; *e.g.,* how does a change in calcification rate affect the ecology and survivorship of an organism? How will ecosystem functions differ between communities with and without calcifying species?
- Improve the accounting of coral reef and open ocean carbonate budgets through combined measurements of seawater chemistry, $CaCO_3$ production, dissolution and accumulation, and, in near-shore environments, bioerosion and offshelf export of $CaCO_3$;
- Quantify and parameterize the mechanisms that contribute to the carbonate system, through biogeochemical and ecological modeling, and apply such modeling to guide future sampling and experimental efforts;
- Develop protocols for the various methodologies used in seawater chemistry and calcification measurements."

Kleypas, J.A., R.A. Feely, V.J. Fabry, C. Langdon, C.L. Sabine, and L.L. Robbins, 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, 88 pp.

Question 7. About one-third of all man-made carbon dioxide emissions are absorbed into the ocean. However, at a certain point the oceans may no longer be able to absorb carbon dioxide at the same rate. If this happens, warming of the atmosphere will increase even more rapidly. Are we close to seeing the rate that the oceans absorb carbon dioxide slow down to a point that our global temperatures increase even faster?

Answer. Several factors may decrease the future effectiveness of the ocean sink for anthropogenic carbon dioxide. The chemical buffer capacity of seawater decreases as the levels of inorganic carbon increase. Warming reduces the solubility of carbon dioxide. Surface warming and increased vertical stratification are also expected to slow ocean circulation, which will reduce oceanic carbon dioxide uptake. Carbon dioxide uptake would also decline if the ocean deep-water circulation in the North Atlantic were to slow dramatically. In numerical models, most of these factors decrease ocean carbon dioxide uptake rates gradually with time. Some effects are already being felt, and their influence will grow with time with global warming and rising atmospheric carbon dioxide.

Question 7a. How does temperature affect the rate at which ocean acidification occurs?

Answer. The dominant factor in ocean acidification is the increase in the amount of dissolved inorganic carbon in seawater. Some researchers have explored the impacts of climate change on ocean acidification, finding relatively small impacts relative to the signal from increasing dissolved inorganic carbon. Temperature plays a key role in determining the chemical impact of acidification. The saturation state of carbonate minerals in seawater depends on temperature. The saturation state of colder waters starts off lower than in warmer waters and will become under-saturated with respect to carbonate minerals before warmer waters.

Question 7b. The Arctic Ocean is becoming warmer and fresher which may slow down thermohaline circulation. What are the implications of these changes on ocean acidification?

Answer. Climate change is expected to warm and freshen the surface ocean in the Arctic and reduce sea-ice cover. The increased vertical stratification will reduce the transport of anthropogenic carbon dioxide into intermediate and deep-waters in the Arctic, reducing the influence of ocean acidification in mid- to deep-waters. In contrast, reduced sea-ice will enhance surface gas exchange, surface water levels of anthropogenic carbon dioxide and acidification.

Question 7c. How does the increase in atmospheric carbon dioxide and subsequent warming affect atmospheric and oceanic circulation? Will the increase in atmospheric and ocean temperatures result in more frequent El Niño's and intense hurricane seasons?

Answer. This a wide-ranging and complex question at the heart of a large research effort on climate change research within the U.S. and internationally. A broad-brush picture of the expected changes in ocean and atmosphere circulation are given in the 4th IPCC Assessment Report that was recently released (IPCC, 2007). A major factor is that global warming of the surface ocean will inject more water vapor into the atmosphere, strengthening the planetary water cycle and potentially providing more energy for storms. The Arctic and land surfaces will warm faster than the ocean, altering the temperature gradients that drive atmospheric circulation and winds. The Arctic will experience a reduction in sea-ice cover, particularly in summer, and a general warming and freshening of surface waters. Warming of the upper-ocean and inputs of additional freshwater at high latitudes will tend to increase vertical stratification of the upper water column and slow exchange between surface and subsurface water masses. Altered wind patterns will also change the location and strength of coastal and open-ocean upwelling.

According to the Summary for Policy Makers for Working Group I, the following more specific trends are expected:

- heat extremes, heat waves and heavy precipitation events will become more likely;
- tropical cyclones (hurricanes and typhoons) will likely be more intense with larger peak wind speeds; there is still considerable debate about whether the number of tropical storms will change;
- the stormtracks for extratropical storms are likely to move poleward, altering precipitation patterns;
- the amount of precipitation will likely increase at high latitudes and decrease at subtropical latitudes; the latter may exacerbate subtropical droughts;

- the meridional overturning circulation and deep water formation in the Atlantic will likely decrease but it is very unlikely to undergo an abrupt transition over this century.

There is less confidence in predictions of expected changes in ocean and atmosphere circulation on more regional scales because the model forecasts differ from climate model to climate model.

Question 7d. Which ocean regions will be first to experience large changes in carbonate chemistry? How long before large changes occur?

Answer. The entire surface ocean is already experiencing changes in carbonate chemistry, and these trends will increase approximately in step with rising atmospheric CO_2 concentrations. When anthropogenic CO_2 dissolves in seawater it decreases pH, increases the partial pressure of carbon dioxide (pCO_2), and increases the concentration of dissolved inorganic carbon (DIC, the sum of all of the different inorganic forms of carbon dioxide, carbonic acid, and its acid-base dissociation products). Except in regions of seasonal and permanent ice-cover, the positive trend in surface water pCO_2 and DIC appears to approximately track the rise in atmospheric CO_2 levels following solubility equilibrium relationships. The magnitude of the pH change depends upon the buffering capacity of seawater; more rapid pH changes occur in colder waters and waters with higher DIC and pCO_2 levels for the same size incremental addition of carbon dioxide.

The penetration of the anthropogenic carbon dioxide signal into the subsurface ocean is controlled by ocean circulation. The concentrations of anthropogenic carbon and perturbations to pH tend to decrease as one looks down the water-column. About half of all the anthropogenic carbon dioxide is found in the upper 400 m (~1,200 feet) of the water column. Elevated levels of anthropogenic carbon are found below that depth in the lower thermocline (400–1000 meters depth) below the surface water convergence zones of the subtropical gyres and Southern Ocean. Anthropogenic carbon is also observed below the thermocline in and downstream of intermediate and deep-water formation regions in the northern North Atlantic and Southern Ocean.

Question 8. How will lower calcification rates, due to an increase in ocean acidification, higher ocean temperatures, and changes in nutrients affect ocean carbon chemistry and carbon export rates?

Answer. Acidification will tend to reduce the calcification in the upper ocean, the sinking flux (export) of particulate inorganic carbon, and the remineralization of particulate inorganic in the subsurface ocean. The effect of acidification on total biological productivity in the surface ocean may be about neutral, as it is likely that non-calcifying organisms may be able to replace calcifying phytoplankton populations that are diminished due to acidification. Organic carbon export to the subsurface ocean via sinking particles is not directly proportional to biological productivity, but depends upon the composition of the food web. Organic matter has a density similar to seawater, and there is evidence indicating that heavier ballast materials, such as carbonate shells, increase organic matter sinking rates. The impact of reduced calcification on the export of organic carbon in the open ocean is less certain, but may also result in a reduction in export.

Reduced inorganic export has the opposite effect as reduced organic carbon export on surface water chemistry and air-sea carbon fluxes. The formation of organic matter lowers seawater dissolved inorganic carbon (DIC) and lowers the partial pressure of carbon dioxide (pCO_2), which governs the air-sea gas exchange of carbon dioxide. A reduction in organic matter export, therefore, would reduce the effectiveness of the biological pump and act to increase surface water and atmospheric CO_2 thus accelerating climate change. The formation of calcium carbonate ($CaCO_3$) or calcification in surface waters lowers both seawater DIC and alkalinity (a measure of the acid-base balance of seawater). For each mole of $CaCO_3$ removed, DIC drops by 1 mole and alkalinity drops by 2 moles. Somewhat counter intuitively, calcification increases pCO_2 because the effect of the alkalinity change outweighs that of DIC. Therefore reduced carbonate export would act to decrease surface water and atmospheric CO_2 thus helping to ameliorate climate change. Preliminary model simulations, however, suggest that the calcification-alkalinity feedback mechanism provides only a small brake on increasing atmospheric carbon dioxide due to fossil fuel combustion.

Question 9. What are the expected changes to the biological pump—the process which transports carbon throughout the ocean—due to the increase in carbon dioxide and what will be the consequences of these changes?

Answer. Rising atmospheric carbon dioxide has two major effects on the ocean biological pump, altered ocean physics and ocean acidification. The impact of ocean acidification is addressed in the answer to question 8 above. Ocean physics will be altered because of carbon dioxide induced global warming and other changes in physical climate. Surface warming globally and larger freshwater inputs at mid- to high-latitudes will increase the vertical stratification of the water column.

Many areas of the tropical and subtropical ocean are nutrient limited, and increased vertical stratification may decrease the supply nutrients to the upper ocean. In these areas, biological productivity and the sinking of organic particles, which drives the biological pump, may drop because of the reduced nutrient supply. One possible complication is nitrogen fixation; most organisms cannot use nitrogen gas, but a small number can convert nitrogen gas into an organic form that is broadly usable. Nitrogen fixation is enhanced in warm, stratified waters and may increase in the future under climate warming. Phytoplankton in some regions at mid- to high-latitude is currently light-limited because of deep mixing. Biological production and particle export may be enhanced in these areas because warming and freshwater inputs will reduce vertical mixing rates and thus light limitation. Model projections suggest that global ocean productivity may not change substantially.

Question 10. Fossil-fuel use is also increasing the amounts of nitric and sulfuric acid deposition in the oceans. How will these elements alter surface seawater alkalinity and pH?

Answer. Fossil fuel combustion releases reactive nitrogen and sulfur to the atmosphere. Some fraction is deposited to the surface ocean as nitric and sulfuric acid, which reduces surface seawater alkalinity. Agriculture releases reactive nitrogen that is deposited to the ocean as ammonia. Because of biogeochemical transformations, the ammonia input also leads to a reduction in ocean alkalinity. The changes in surface seawater chemistry will lead to lower seawater pH levels.

Question 10a. Will the impacts of these elements differ in coastal waters versus open ocean and how may they affect marine ecosystems?

Answer. The effects depend upon the deposition rates of reactive nitrogen and sulfur, which are highest in coastal regions and open-ocean areas downwind of the major source regions in eastern North America, western Europe, and south and east Asia. The effects of acidification from reactive nitrogen and sulfur deposition will be similar to that caused by oceanic uptake of fossil-fuel carbon dioxide. Coastal regions may be more vulnerable to elevated acidification because of other human perturbations (local pollution, nutrient runoff, overfishing). Reactive nitrogen deposited from the atmosphere will also stimulate ocean photosynthesis because nitrate and ammonia are nutrients. Similar to excess nitrogen from river and groundwater runoff, the resulting nutrient fertilization (eutrophication) may lead to low oxygen zones and blooms of harmful algae.

Question 11. During the hearing a question was raised regarding the global average increase in ocean temperature of 0.04° C. It is well known that the largest increases in ocean temperature are in the surface waters and this plays a large role in the Earth's heat budget. Can you please explain how significant the warming has been in the surface waters and what the implications have been for increased sea surface temperature as it relates to hurricane intensity, El Niño, drought, and other extreme weather events? Can you highlight different regions that have experienced large increases in surface water temperature and how much the surface waters have warmed?

Answer. Ocean warming is indeed concentrated in the upper part of the water column. The global average temperature increase of 0.037 deg. C reported by Levitus *et al.,* 2005 applies to a depth range from the surface to 3,000m (~10,000 feet) for time interval of (1994–98) relative to (1955–59). In their analysis, they also report an average temperature increase almost 5 times as large (0.171 deg. C) for the upper water column 0–300m (~1,000 feet) over the time period 1955–2003. As shown in a table below, Atlantic temperatures in the 0–300m depth range increased faster than the global trend.

Sea surface temperature also increased at a rate comparable to or faster than the 0–300m trend. Hansen *et al.,* (2005) present a spatial map of the change in sea surface temperature for the period (2001–2005) relative to a base period of 1951–1980. They find significant areas of the Atlantic, Indian Ocean and tropical Pacific where the sea surface temperature increased by between 0.4 to 0.8 deg. C. Examining modern (2001–2005) sea surface temperature changes relative to preindustrial conditions (1870–1900) reveals warmer sea surface temperatures almost everywhere in the ocean, with larger regions showing temperature increases of more than 0.5 deg. C.

Higher sea surface temperatures increase the transfer of heat and moisture from the ocean to the atmosphere. Higher sea surface temperatures have been proposed as a mechanism for strengthening the intensity of tropical cyclones (typhoons and hurricanes), and variations in sea surface temperature have been linked to periods of both drought and flooding on land. Future climate model projections suggest that increasing sea surface temperature and climate warming will drive increased precipitation at high latitude, decreased precipitation in the subtropics (and possible droughts) and a general increase in the frequency of extreme precipitation events. The link between sea surface temperature and El Niño is somewhat more subtle as El Niño conditions in the tropical Pacific themselves results in elevated sea surface temperatures in the tropical Pacific and along the West Coast of North America. Through atmospheric teleconnections, El Niño events also alter sea surface temperatures over much of the world ocean.

Levitus, S., J. Antonov, and T. Boyer (2005), Warming of the world ocean, 1955–2003, Geophys. Res. Lett., 32, L02604, doi: 10.1029/2004GL021592.

Hansen, J., M. Sato, R. Ruedy, K. Lo, D.W. Lea, and M. Medina-Elizade, 2006: Global temperature change, *Proceedings of the National Academy of Science,* 103, 14288–14293, doi: 10.1073/pnas.0606291103.

Table T1. Change in ocean mean temperature (deg. C) as determined by the linear trend for the world ocean and individual basins. (Levitus *et al.,* 2005; supplementary material).

Ocean basin	Change in mean temperature 0–300 m (1955–2003) (deg. C)
World Ocean	0.171
N. Hem.	0.188
S. Hem.	0.159
Atlantic	0.297
N. Atl.	0.354
S. Atl.	0.233
Pacific	0.112
N. Pac.	0.093
S. Pac.	0.127
Indian	0.150
N. Ind.	0.125
S. Ind.	0.154

Response to Written Questions Submitted by Hon. Daniel K. Inouye to Richard A. Feely, Ph.D.

Question 1. I am pleased to learn that NOAA has been working with other agencies, including NASA and NSF, to formalize a Federal research effort, including research on ocean acidification. Could you describe the current Federal interagency research program and how it might be strengthened?

Answer. While there is no formal Federal interagency research program, NOAA and other Federal agencies (*e.g.,* the U.S. Geological Survey (USGS), the National Science Foundation (NSF), and the National Aeronautics and Space Administration (NASA)) are currently in the process of developing a formal research and/or monitoring program to address ocean acidification. Over the past two decades, a number of large-scale international ocean research programs have documented global increases in the amount of carbon dioxide (CO_2) in the world's oceans. These programs, co-sponsored by NSF, NOAA and the Department of Energy, include the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Study (JGOFS) Global CO_2 Survey and the CLIVAR/CO_2 Repeat Hydrography Program. The increase in ocean CO_2 concentrations and corresponding decreases in pH levels (ocean acidification) occur in direct response to rising levels of atmospheric CO_2 and will affect some of the most fundamental processes of the sea in coming decades. In recent years, the rapidly emerging issue of ocean acidification has garnered considerable interest across the scientific community, and NOAA, NSF and NASA have been working to identify what existing capabilities can be better tailored to monitor and understand ocean acidification. NOAA and NSF have played an important joint role in identifying the current extent of ocean acidification through ocean observations. NOAA has also been involved in using environmental models to forecast ocean acidification levels over the coming century under a variety of CO_2 emission scenarios, and has begun investigating the possible ecosystem consequences through research studies.

Detailed in the following discussion is an overview of various NOAA programs, technologies, and research efforts that have yielded findings deemed relevant to ocean acidification or have recently been initiated with the intent of addressing the many remaining uncertainties identified by the scientific community. These examples include some description of current Federal interagency efforts, as well as collaboration with non-Federal/academic institutions.

NOAA Collaborative Workshops

In 2005, NOAA, USGS, and NSF jointly sponsored a workshop focused on ocean acidification, which resulted in a report entitled *Impacts of Increasing Ocean Acidification on Coral Reefs and Other Marine Calcifiers: A Guide for Future Research.* The workshop sought to summarize existing knowledge on ocean acidification, identify the most pressing scientific issues, and identify future research strategies over the next 10 years. The report concluded that ocean acidification will significantly impact biological systems in the upper ocean with adverse responses being observed in most organisms studied that rely on calcium carbonate to build their skeletal structures (calcifying organisms or calcifiers; *e.g.,* corals). The report also identified an extensive list of remaining knowledge gaps and research needs with regards to ocean acidification. Among the list offered by the workshop report was a recommendation to better characterize the carbon chemistry on coral reefs, including long-term monitoring of the response of these sensitive ecosystems to ocean acidification.

Observations Relevant to Ocean Acidification

Global CO_2 Surveys

NOAA has contributed to several international and national research programs that have offered important findings relevant to ocean acidification. These programs include the World Ocean Circulation Experiment (WOCE), the Joint Global Ocean Flux Study (JGOFS), the joint NOAA/NSF CLIVAR/CO_2 Repeat Hydrography Program, the Tropical Atmosphere Ocean (TAO) array, and the Global Ocean Observing System (GOOS), as well as data collected through NOAA-supported hydrostations, mooring stations, and vessel observations. These research programs provide the most accurate and comprehensive view of the global ocean carbon cycle to date. NOAA funded a 5-year WOCE/JGOFS data analysis effort that culminated in NOAA's Pacific Marine Environmental Lab (PMEL) lead-authoring two important *Science* articles highlighting ocean acidification in July 2004. While one article detailed the ocean's role as an important sink for anthropogenic carbon dioxide, (Sabine *et al.,* 2004), the other described the impact that this additional carbon exerts on the ocean's chemistry and its potential long-term consequences for marine ecosystems (Feely *et al.,* 2004).

Sabine *et al.* (2004) inventoried the amount of anthropogenic CO_2 (*i.e.,* fossil-fuel and cement-manufacturing emissions of carbon dioxide) that has been absorbed by the world's oceans. Results from the inventory demonstrated that about 120 billion metric tons of carbon as CO_2 (roughly half of the fossil-fuel CO_2 released since the 1800s) has been absorbed by the ocean. Much of this added carbon has remained concentrated in surface waters as the mixing rate of the oceans is on the order of several thousand years.

In addition to the WOCE/JGOFS studies, NOAA, together with the Japan Agency for Marine-earth Science and Technology and France's L'Institut de recherche pour le développment, has jointly funded the TAO array. The TAO array consists of approximately 70 moorings in the tropical Pacific Ocean and is an important part of the Global Ocean Observing System (GOOS). These oceanic hydrostations and mooring systems provide temporal data that helps NOAA discern important seasonal and decadal variability. To better ascertain the spatial variability in oceanic carbon uptake, NOAA has collaborated with academic partners since 1985 to outfit research and commercial vessels with automated CO_2 sensors. The intent of these observations has primarily been to derive estimates of CO_2 exchange between the atmosphere and the surface waters of the ocean.

Fixed Buoys

As mentioned above, the TAO array consists of approximately 70 moorings in the Pacific Ocean that transmit ocean and climate data in real-time for the purposes of tracking El Niño events. NOAA's Pacific Marine Environmental Laboratory (PMEL) has worked closely with the Monterey Bay Aquarium Research Institute to outfit several of these moorings with CO_2 sensors. While the coverage of these buoys is limited to the Pacific Ocean, and therefore do not fully capture the broad and complex system of global CO_2 absorption in the ocean, they provide consistent data that helps NOAA discern important variability season-to-season and decade-to-decade.

In response to the 2005 ocean acidification workshop, NOAA deployed a series of fixed buoys and augmented existing monitoring stations to accommodate CO_2 sensors deployed at a handful of U.S. coral reefs. The NOAA Coral Reef Conservation Program, together with researchers at the NOAA Atlantic Oceanographic and Meteorological Laboratory (AOML) and the University of Miami, has experimented with the deployment of commercially available CO_2 sensors on NOAA Integrated Coral Observing Network (ICON) stations at two locations in the Caribbean. NOAA PMEL has also developed an advanced CO_2 mooring system, of which four have been deployed in coastal waters. While these observing systems are preliminary, they have offered important insight into the CO_2 variability of these waters which contrast sharply to that of offshore waters. The CO_2 measurements at one of the Hawaii moorings have been compared against those recorded offshore at a long-term hydrostation. Similarly, observations made in Puerto Rico have been compared against offshore estimates derived using remote sensing. In both cases, the variability of CO_2 levels in waters overlying coral reefs is shown to be considerably higher on daily, seasonal, and interannual scales than in offshore waters that have typically been the focus of ocean acidification models. Furthermore, these coastal waters consistently have higher CO_2 levels than that of offshore waters, suggesting these systems may exceed critical levels of CO_2 sooner than has been demonstrated in most ocean acidification models. What those precise thresholds might be is an area of continued investigation within the scientific community and NOAA will need to collect additional data necessary to achieve any firm conclusion on the matter.

Satellite Observations

Other observing efforts being advanced at NOAA with important relevance to ocean acidification include the application of satellite remote sensing to supplement ship and buoy observations of surface ocean carbon chemistry. While ship observations provide reliable and accurate measurements of surface ocean CO_2, and offer considerably greater spatial coverage than that provided by moored instruments, they lack the temporal resolution of fixed platforms (*i.e.,* observations over time in one location) and provide relatively limited regional coverage. Such observations can be supplemented by satellite remote sensing. NOAA has worked to derive algorithms relating environmental parameters that can be remotely sensed to *in situ* observations of carbon measurements. NOAA continues to work to improve the reliability and accuracy of these models and improve the data delivery to the community. Such models are being experimentally coupled to NOAA's ICON station CO_2 monitoring network in the hopes of deriving a tool for coral reef management to monitor the response of coral reefs to ocean acidification.

All of these observing networks and platforms have not been designed to specifically address ocean acidification *per se,* which demands a more comprehensive measurement of ocean carbon chemistry. Measurement of ocean acidity requires *in situ* technology, which NOAA is currently testing. Such advanced observations are required to fully model the magnitude, rate and severity of ocean acidification.

Research Efforts and Ocean Acidification

Northwest

NOAA's Northwest Fisheries Science Center (NWFSC) has begun collaborating with the University of Washington on ocean acidification research relevant to Pacific fisheries. In September 2006, the NWFSC began some initial modeling studies of possible consequences of ocean acidification on food webs. Two ongoing research projects are focused in Puget Sound and the Northeast Pacific shelf. Both projects are investigating how likely changes in calcifier populations at all trophic levels will impact the food web. Many organisms are expected to be affected, including coccolithophores (phytoplankton made of calcium carbonate), pteropods (a form of shelled zooplankton), cold-water corals, and echinoderm larvae (*e.g.,* sea urchins and sea stars). From past research on acid rain there is also evidence of acidification's effect on animal behavior and homing, an area where the NWFSC has also initiated some preliminary fisheries-related lab studies. Further investigations could include questions of how changing ocean chemistry could impact how pollutants are taken up by the ocean, their chemical form, and their impact on ocean life.

Alaska

NOAA's Alaska Fisheries Science Center (AKFSC) has started research on the effects of decreased pH on red king crab larval growth and survival. This project was a pilot study designed to test the ability to culture crab larvae under experimentally manipulated pH conditions. Preliminary results showed ~15 percent reduction in growth and ~67 percent reduction in survival when pH was reduced 0.5 units. Lab work to determine pH effects on the calcium content of exoskeletons is ongoing.

Southwest

NOAA's Southwest Fisheries Science Center (SWFSC), as part of the U.S. Antarctic Marine Living Resource (AMLR) Program, also collected water and zooplankton samples to investigate effects of ocean acidification in the Southern Ocean during its 2007 krill biomass survey. These samples comprise the beginning of NOAA's research to understand the impact of changing pH in the South Shetland Islands. Given that in the foreseeable future CO_2 levels are likely to rise, the degree of supersaturation for both aragonite and calcite (two calcium carbonate ($CaCO_3$) polymorphs) will decline. This could impact both invertebrate and vertebrate communities. Aragonite and calcite are the building blocks for skeletal material and shells of many organisms and lower concentrations of the building blocks of these minerals in seawater will increase the energy needed by organisms to form their skeletal and shell structures. This increased energy need can stress the organisms' physiology. Our data collection and analysis efforts will provide information necessary for the development of mitigation options. This work is being completed in collaboration with scientists from NOAA PMEL and California State University San Marcos, who will provide the analytical capacity lacked by the AMLR Program.

National

NOAA Sea Grant serves as a unifying mechanism within NOAA to engage top universities to assist NOAA in meeting its mission goals and responsibilities. Sea Grant conducts research, extension, education, and communication activities, with a goal to achieve a sustainable environment and to encourage the responsible use of America's coastal, ocean, and Great Lakes resources. Sea Grant has supported research on the affects of ocean acidification on coral reefs in Hawaii.

Ocean Acidification Modeling

NOAA's Geophysical Fluid Dynamics Laboratory (GFDL) works cooperatively throughout the agency to advance its expert assessment of changes in national and global climate through research, improved models, and products. GFDL participated in the 1995 Ocean-Carbon Cycle Model Intercomparison Project (OCMIP), which developed an international collaboration to improve the predictive capacity of ocean-carbon cycle models through evaluation and intercomparison. After a 3-year pilot study with 4 models (OCMIP–1), a second phase of study (OCMIP–2; 1998–2002) involved 13 international modeling groups and data specialists taking on a more detailed effort. The models developed by these groups were used to forecast how ocean chemistry could change under the 'business-as-usual' scenario (as defined by the Intergovernmental Panel on Climate Change) for future emissions of anthropogenic carbon dioxide. Under such a scenario, the models predict that the surface waters of the Southern Ocean will become chemically unfavorable to some forms of calcium carbonate by the year 2050 (*i.e.,* the pH of the surface waters will be too low to allow solid calcium carbonate to form). By 2100, such conditions could extend throughout the entire Southern Ocean and into the subarctic Pacific Ocean (Orr *et al.,* 2005). When live pteropods were subjected to chemical conditions predicted by these models, their shells (calcium carbonate) began to dissolve. The findings of the study concluded that conditions detrimental to high-latitude ecosystems could develop within decades.

NOAA can strengthen the existing efforts by improving its understanding of the climate-ecosystem linkages to better predict ecosystem (and living marine resource) impacts and adaptations to climate change. Specifically, NOAA can enhance its monitoring of living marine resource population demographics, distributions, migrations, and health.

Additionally, NOAA can translate climate information from global to regional levels to facilitate management of ecosystem issues at the regional level.

Question 2. Are there international efforts currently underway or in development to address the issue of ocean acidification and is the United States involved in such efforts?

Answer. In addition to the efforts detailed in response to Question 1 (above), over the past year NOAA scientists have been interacting with their colleagues from Europe and Asia on the development of international cooperative research efforts on ocean acidification. At the international level, research on ocean acidification is being implemented through the Integrated Marine Biogeochemistry and Ecosystem Research project and Surface Ocean Lower-Atmosphere Study. Senior NOAA and academic scientists have been invited by their European counterparts to contribute to the planning and implementation of the European Project on Ocean Acidification. Similar negotiations are presently underway with colleagues from Japan and Korea.

Question 3. Coral reefs are not just critical habitat for fish. In my state of Hawaii, they are also an economic engine supporting both fishing and tourism. Is ocean acidification or the increase in sea temperature the more pressing issue for protecting and preserving Hawaii's coral reefs and other marine resources and why?

Answer. While our present understanding of coral bleaching and ocean acidification is at an early stage of development, the research results thus far indicate that increases in sea surface temperature and changes in ocean chemistry both present considerable risk to the future sustainability of coral reef habitat and the eco-services they provide to Hawaii. Both surface temperature and ocean chemistry are related to changes in atmospheric carbon dioxide concentrations (directly in the case of ocean acidification) and so the two issues are inextricably linked. The prevailing expectation of the scientific community is that, should sea surface temperatures continue to rise, coral bleaching will continue to occur with greater frequency and intensity. The resilience of reefs against threats posed by rising temperatures is likely to be compromised by their declining ability to build reefs as a result of ocean acidification. While there is much that remains unknown with regards to how these two processes interact, it is likely the impact of the two threats together will be greater than the sum of the two separate impacts.

Question 4. How can we incorporate actions to address these issues into an overall management strategy for protecting Hawaii's corals and other marine resources?

Answer. NOAA is committed to an ecosystem approach to resource management that addresses the many simultaneous pressures affecting ecosystems. The various effects of climate change on wildlife and oceans are interrelated. While the strategies outlined in the 2006 publication *A Reef Manager's Guide to Coral Bleaching* (produced by NOAA, the Environmental Protection Agency, the Australian Great Barrier Reef Marine Park Authority, and the International Union for the Conservation of Nature) were designed to address coral bleaching in Hawaii and other federally-protected coral reef ecosystems, many of the strategies in the guide will support reef resilience in the face of ocean acidification. Additional research is needed to fully characterize the threat of ocean acidification to coral reef communities and to identify and devise specific adaptive management strategies.

Once identified, adaptive strategies that plan for climate change impacts can be applied to the ocean and coastal environment through a variety of mechanisms, including incentives and disincentives, policies and regulations, and public outreach and education. A number of NOAA's research programs have also begun to consider how climate change, and specifically ocean acidification scenarios, may impact many regulated species—particularly bivalve mollusks, crustaceans, and species dependent on shallow-water coral reefs. Over 50 percent of the value of U.S. fisheries derives from clams, scallops, and oysters, and various species of shrimp, crab, and lobster. These shellfish are thought to be particularly vulnerable to the effects of reduced levels of calcium carbonate building blocks in the oceans due to increasing acidity. NOAA's National Marine Fisheries Service has initiated a few pilot studies to attempt to understand these impacts.

Question 5. Dr. Feely, under a "business as usual" scenario of greenhouse gas emissions, what do you project will be the impacts on coral reefs and other marine resources?

Answer. The recently released Summary for Policy Makers in the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report on Impacts, Vulnerability and Adaptation to Climate Change found that under a business as usual scenario:

- The resilience of many ecosystems is likely to be exceeded this century by an unprecedented combination of climate change, associated disturbances (*e.g.,* flooding, drought, ocean acidification), and other global change drivers (*e.g.,* land use change, pollution, over-exploitation of resources).
- For increases in global average temperature exceeding 1.5–2.5° C and in concomitant atmospheric carbon dioxide concentrations, there are projected to be major changes in ecosystem structure and function, species' ecological interactions, and species' geographic ranges, with predominantly negative consequences for biodiversity, and ecosystem goods and services, *e.g.,* food supply.

As described in the response to Question 1, NOAA's Geophysical Fluid Dynamics Laboratory contributed to the Ocean-Carbon Cycle Model Intercomparison Project. The models that resulted from this project were used to forecast how ocean chemistry could change under the 'business-as-usual' scenario (as defined by the Intergovernmental Panel on Climate Change) for future emissions of anthropogenic carbon dioxide. Under such a scenario, the models predict that the surface waters of the Southern Ocean will become chemically unfavorable to some forms of calcium carbonate by the year 2050. By 2100, such conditions could extend throughout the entire Southern Ocean and into the subarctic Pacific Ocean.

Recent work indicates that corals in the 21st century will have to adapt to temperature increases of at least 0.4 degrees Fahrenheit per decade to survive the increasing frequency and intensity of coral bleaching that we expect in the next few decades (Donner *et al.,* 2005). Unfortunately, ongoing studies have not yet shown that corals have the ability to make physiological or evolutionary changes at that rate. Limited latitudinal expansion of coral distributions is possible and may be occurring in one case (Precht and Aronson, 2006). However, corals in higher latitudes are likely to encounter lower pH waters (ocean acidification) and their skeletal growth rate may be depressed (Guinotte *et al.,* 2003; Guinotte *et al.,* 2006).

Question 6. What if we stabilized our greenhouse gas concentrations at between 445 and 710 parts per million?

Answer. According to the 4th Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) Working Group II, the mitigation measure of reducing anthropogenic greenhouse gas emission can reduce a number of projected climate change impacts. Reducing greenhouse gas emissions below 445 ppm would specifically act to:

- Reduce the level of ocean acidification affecting coral reefs and other calcifying plankton and shellfish.
- Reduce the severity of coral bleaching events.

Note that even reducing greenhouse gas emissions to 445 ppm is projected only to reduce the severity of coral bleaching events, as opposed to preventing those events. In addition, because of the inertia in the climate system, it would take several decades before any benefits from mitigation efforts materialize. According to the IPCC, even if complete mitigation were put into place immediately (meaning even if anthropogenic carbon dioxide emissions were immediately reduced to zero), because of existing carbon dioxide in the system, we are committed to a 0.6° C temperature change over the next 50 years.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. MARIA CANTWELL TO RICHARD A. FEELY, PH.D.

Question 1. In your testimony, you discussed the potential impacts that ocean acidification might have on coldwater species in the Bering Sea. Along much of the West Coast, we are wrestling with the recovery of endangered salmon. Salmon are, of course, both commercially and culturally important, and they're also a critical part of the food web for the endangered Puget Sound Southern Resident Orca. From your research, will ocean acidification place these species in further jeopardy? If so, specifically how might this occur?

Answer. Our understanding of the connections between ocean acidification and the marine food chain is in a very early stage of development. Scientists have observed a reduction in the ability of marine algae and free-floating plants and animals to produce protective carbonate shells when exposed to decreasing pH (Feely *et al.,* 2004; Orr *et al.,* 2005). 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 mackerel, pollock, herring, and cod. Other marine calcifiers, such as coccolithophores (microscopic algae), foraminifera (microscopic protozoans), and mollusks (snails, clams, and mussels) also exhibit a general decline in their ability to produce their shells with decreasing pH (Kleypas *et al.,* 2006). The concern among scientists is that as the food sources for the salmon and whales are reduced in abundance, those populations will also decline.

Question 2. The most rigorous mitigation goal in the recent summary report by the Intergovernmental Panel on Climate Change is to stabilize atmospheric greenhouse gas levels between 445 and 710 parts per million by 2030. But given that the current concentrations of atmospheric carbon are estimated at 380 parts per million, shouldn't this target be set at a much lower level if we are to effectively address climate change? What is the expected temperature increase of this range? What would be the impacts on our ocean resources if we were to reach these emissions levels?

Answer. According to the 4th Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) Working Group II, the mitigation measure of reducing anthropogenic greenhouse gas emission can reduce a number of projected climate change impacts. Reducing greenhouse gas emissions below 445 ppm would specifically act to:

- Limit temperature increase to 2.0–2.4° C
- Reduce the future severity of drought in the U.S.

- Reduce the level of ocean acidification affecting coral reefs and other calcifying plankton and shellfish.
- Reduce the severity of coral bleaching events (*e.g.,* a 1–3° C increase in global temperature would result in more bleaching events with small recovery times, whereas an increase of 2.5–3.0° C could result in widespread mortality).

Because of the inertia in the climate system, it would take several decades before any benefits from mitigation efforts materialize. According to IPCC, even if complete mitigation were put into place immediately (meaning if anthropogenic carbon dioxide emissions were immediately reduced to zero), because of existing carbon dioxide in the system, we are committed to a 0.6° C temperature change over the next 50 years. In addition, it is important to note that the IPCC summary does not explicitly predict the magnitude and timing of consequences because these depend on the amount and rate of CO_2 emissions and subsequent warming, and, in some cases, on society's ability to adapt.

Question 3. What are the potential impacts of some of the currently proposed climate change mitigation strategies on the marine environment—such as iron stimulated plankton blooms or injection of CO_2 into sea sediments?

Answer. The broad potential impacts of climate change mitigation strategies are discussed in answer to question 2 (above). In 2005 the Intergovernmental Panel on Climate Change (IPCC) published a special report on Carbon Dioxide Capture and Storage (*http://www.ipcc.ch/activity/srccs/index.htm*), but the IPCC report does not address biological approaches for carbon capture and storage in the ocean, such as iron-stimulated plankton blooms. There have been several small research projects that have demonstrated that iron fertilization can cause a phytoplankton bloom in certain regions of the ocean. However, current scientific evidence indicates that large-scale iron fertilization will not significantly increase carbon transfer into the deep ocean or lower atmospheric CO_2. Furthermore, there may be negative impacts of iron fertilization including dissolved oxygen depletion, altered trace gas emissions that affect climate and air quality, changes in biodiversity, and decreased productivity in other oceanic regions.

In 2005 the Intergovernmental Panel on Climate Change (IPCC) special report on Carbon Dioxide Capture and Storage, one chapter is devoted to ocean storage of CO_2. This report noted that deep ocean injection is technically possible and would isolate the CO_2 from the atmosphere for several hundreds of years. The fraction of CO_2 retained in the ocean over time generally tends to be longer with deeper injection, but the cost of placing the CO_2 deeper is also higher. Injection of a few billion metric tons of CO_2 would produce a measurable change in ocean chemistry in the region surrounding the injection, whereas injection of hundreds of billions of metric tons of CO_2 would eventually produce measurable changes over the entire ocean volume. Deep-ocean CO_2 injection would introduce anthropogenic CO_2 to regions of the deep ocean that have not yet been exposed to elevated CO_2. In particular, the areas around the injection sites would experience CO_2 levels far in excess of anything that would result from the natural uptake of anthropogenic CO_2.

Question 4. Given your understanding of ocean acidification, does using the ocean to store CO_2 make good policy sense, or would we just be creating additional problems? Are there safe and effective ways to use the ocean to mitigate the effects of excess carbon dioxide in the atmosphere?

Answer. The IPCC report mentioned in answer to the question above (Carbon Dioxide Capture and Storage: *http://www.ipcc.ch/activity/srccs/index.htm*) gives several examples of viable carbon storage options, such as the injection of CO_2 into geological reservoirs. These options appear to have potentially longer storage times and fewer potential environmental impacts than purposeful ocean carbon storage. The oceans will continue to take up anthropogenic CO_2 for at least the next few thousand years, thus acting as a natural mitigation pathway. This natural uptake will have environmental consequences that we are still trying to understand. At this point, it does not seem to make sense scientifically to exacerbate this by accelerating the process and potentially introduce additional unknown oceanographic and ecological consequences to this valuable resource. Many scientists are also concerned that such fertilization experiments may have the unintended consequence of causing harmful algal blooms, sometimes known as "red tides."

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. FRANK R. LAUTENBERG TO RICHARD A. FEELY, PH.D.

Question 1. According to NOAA, about 4,000 species of fish, including approximately half of all federally-managed fisheries, depend on coral reefs and related habitats for a portion of their life cycles, and the National Marine Fisheries Service estimates that the value of U.S. fisheries from coral reefs exceeds $100 million. Will corals and plankton be able to survive or adapt to more acidic waters in our oceans?

Answer. 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). By mid-century, coral reefs may erode faster than they can be rebuilt potentially making them less resilient to other environmental stresses (*e.g.,* disease, bleaching). This threat to coral reefs could compromise the long-term viability of these ecosystems, perhaps impacting the thousands of species and over one billion people that depend on coral reefs. Decreased calcification rates, as a result of ocean acidification (decreased pH), may also compromise the fitness or success of these organisms and could shift the competitive advantage toward organisms that are not dependent on calcium carbonate ($CaCO_3$). Carbonate structures are likely to be weaker and more susceptible to dissolution and erosion as a result of ocean acidification. In long-term experiments, corals that have been grown under lower pH conditions for periods longer than 1 year have not shown any ability to adapt their calcification rates to the low pH levels.

With respect to planktonic calcifiers (free-floating organisms that rely on calcium carbonate), including the coccolithophores, foraminifera, and pteropods, each group has been shown to respond negatively to increases in CO_2 levels. However, most studies of the impacts of ocean acidification have been performed on bloom-forming coccolithophores, and there are very limited observations of other planktonic groups. If reduced calcification rates contribute to a decrease in a calcifying organism's fitness or survivorship, then such calcareous species may undergo shifts in their latitudinal distributions and/or vertical depth ranges as the CO_2 chemistry of seawater changes. Long-term impacts of elevated CO_2 on reproduction, growth, and survivorship of planktonic calcifying organisms have not been investigated. Existing studies on the impacts of ocean acidification on calcareous plankton have been short-term experiments, ranging from hours to weeks. Chronic exposure to increased CO_2 may have complex effects on the growth and reproductive success of $CaCO_3$-secreting plankton.

Question 1a. If they cannot, what are the implications for other marine species and the ocean's food chain?

Answer. The loss of corals and other calcifying species could have dramatic consequences to marine ecosystems and the human systems that depend on them. Many reef organisms are dependent on coral reefs for their livelihood (Kleypas *et al.,* 2006). Organisms that die out locally during coral bleaching events are likely to be lost. Others will suffer population drops as erosion of reefs reduces or eliminates the habitats in which they live. Changes in ocean pH may also affect reproductive success of commercially important species by reducing demersal egg adhesion or the fertilization success of eggs broadcast into the ocean.

Some calcifying planktonic species affected by ocean acidification are key food sources for commercially-targeted fish, such as juvenile salmon, mackerel, pollock, herring and cod. Therefore, ocean acidification may reduce the abundance of food for these key species at the base of the food chain. The concern among scientists is that as the food sources for the salmon and whales are reduced in abundance, those populations will also decline.

The economic implications of these types of losses will likely be similar to those during coral bleaching events. A study discussed in *A Reef Manager's Guide to Coral Bleaching* (Cesar *et al.,* 2002) indicates that the 1998 bleaching in the western Indian Ocean cost U.S. $71.5 million to the Seychelles, U.S. $47.2 million to Kenya, and U.S. $39.9 million to Zanzibar (in Tanzania).

Question 1b. Species have migrated in response to ocean temperature changes. Will marine organisms migrate to avoid acidification?

Answer. Shallow-water corals are generally limited by water temperatures and visibility (as clear water is necessary to allow sunlight to penetrate for photosynthesis). It is possible that corals will expand poleward as long as proper substrates, temperatures, and clear water are present. Unfortunately, it takes hundreds to thousands of years for reefs to develop. Additionally, many corals grow at much slower speeds (spreading through sexual reproduction and larval transport) than others coral species. The result is that non-reef building invading organisms may take over reefs, while slower growing corals that can be the most important reefbuilders are not able to keep pace with the growth of the non-reef building species. However, even if corals move poleward, it is the higher latitudes that are most affected by ocean acidification. While advancing to high latitudes might stave off thermal stress for a select set of low productivity corals, these systems would likely be subjected to even slower rates of reef building due to ocean acidification. Modern reef systems do not extend to high latitudes in part due to the relatively low pH of these high latitude waters (Guinotte *et al.,* 2003).

Question 2. There have been ocean acidification events in the past that have resulted in the disappearance of marine organisms, including corals. What does the fossil record reveal about the adaptation of marine organisms to changes in ocean acidification? How long did it take for corals and other marine organisms to recover from the acidification events in the past?

Answer. Paleontological studies of coral reef communities before and after these periods show that many species of corals went extinct during periods of high atmospheric and oceanic carbon dioxide. For example, studies indicate that 98 percent of coral species were lost during the extinction at the end of the Triassic and corals did not reappear in the fossil record for 8–10 million years (Stanley, 2006).

The few surviving species took millions of years to evolve to fill the niches left open by the loss of so many corals during these events. Even then, most reefs were dominated by bivalves (clam-like organisms) that later went extinct during the next high carbon dioxide period. That next extinction lasted 17 million years.

Question 3. You indicate in your statement that "the atmospheric concentration of carbon dioxide is now higher than experienced on Earth for at least 800,000 years and is expected to continue to rise . . . the oceans are absorbing increasing amounts of carbon dioxide . . . and the chemical changes in seawater resulting from the absorption of carbon dioxide are lowering seawater pH." Have scientists determined a dangerous level of pH that we need to avoid?

Answer. In order to prevent disruption of the calcification of marine organisms and the resultant risk of fundamentally altering marine food webs, the German Council on Global Change (2006) recommended that the pH of near surface waters should not drop more than 0.2 units below the pre-industrial average value in any large ocean region. While that may seem like a small change, it is important to note that pH units are on a logarithmic scale. This means each whole pH value below 7 is ten times more acidic than the next higher value. For example, pH 4 is ten times more acidic than pH 5 and 100 times more acidic than pH 6. A pH drop of 0.2 units would correspond to an increase in the hydrogen ion (H^+) concentration of around 60 percent compared to pre-industrial values. The decrease in pH so far of 0.11 units since industrialization corresponds to a rise of the H^+ concentration of around 30 percent. The present average pH value of the ocean surface layer is 8.07.

Question 3a. At the current rate of carbon dioxide emissions, how long will it take for the oceans to reach a dangerous level of pH?

Answer. At the present rate of carbon dioxide emissions, we will see a pH drop of 0.2 units from the pre-industrial values by about 2050 (500 ppm CO_2 in the atmosphere). According to simulations by Caldeira and Wickett (2005), a stabilization of the atmospheric CO_2 concentration of 540 ppm by the year 2100 would lead to a global average surface ocean pH decrease of 0.23 compared to the pre-industrial level. Thus, an atmospheric CO_2 concentration of 540 ppm would already exceed the acidification limit of 0.2 units.

Question 3b. Have scientists determined at what level of carbon dioxide concentrations we need to maintain in order to avoid this dangerous level of pH?

Answer. As stated in Question 3 above, the German Council on Global Change (2006) recommended that the pH of near surface waters should not drop more than 0.2 units (<500 ppm CO_2 in the atmosphere) below the pre-industrial average value in any large ocean region.

The largest threat to marine organisms due to ocean acidification is related to the solubility of calcium carbonate, which affects the presence of the carbonate minerals calcite and aragonite. Calcite and aragonite are needed for the construction of shells and skeletal structures. Calcifying marine organisms are important components of marine ecosystems, so their endangerment would have a large impact on economically and socially important marine resources. The German Council on Global Change (2006) states "If the concentration of carbonate ion falls below the critical value of 66 µmol per kilogram, then the seawater is no longer saturated with respect to aragonite, and marine organisms can no longer build their aragonite shells" (Schubert *et al.,* 2006). The danger of undersaturation for aragonite is especially present in the high northern and southern latitudes, and in strong upwelling regions.

Question 4. In light of the latest findings published last month in the journal *Science* in which the biological consumption and remineralization of carbon in the "twilight zone"—a zone in the ocean where some sunlight reaches but not enough for photosynthesis to occur at ocean depths between about 660–3,300 feet—actually reduces the efficiency of sequestration (Buesseler, *et al., Science* 316, 567, 2007). What does this mean for the future of carbon sequestration in our ocean if carbon is recycled back into the surface ocean and atmosphere faster than originally thought?

Answer. The significance of the Buesseler *et al.* (2007) article is that much of the carbon that is sequestered in marine organic matter in the surface euphotic zone is remineralized in the twilight zone and returned to the atmosphere at some later date due to upwelling. The farther down in the ocean this organic carbon remineralization occurs, the longer it takes for the CO_2 to be returned back to the atmosphere. Consequently, the approach of using iron-fertilization as a mechanism for sequestering organic carbon in the oceans may be less inefficient than previously thought because of this remineralization mechanism.

Question 4a. Do scientists know how much carbon sequestered to the deep ocean is being overestimated?

Answer. At the present, this is an area of active scientific research because the present carbon reminearlization estimates have very large uncertainties. In the study discussed above (Buesseler *et al.*) point out that the uncertainty in the estimates of carbon remineralization is as high as 3 Pg C $year^{-1}$, which is more than our best estimate of the anthropogenic carbon uptake at the surface!

Question 4b. How has this changed what scientists think about how long carbon dioxide will be naturally sequestered and how long it will take material to resurface from the twilight zone?

Answer. The Buesseler *et al.* (*Science* 316, 567, 2007) article points to the need for more research on the nature and rates of organic matter remineralization processes in the twilight zone. We need to know if ocean acidification will enhance the process of remineralization in shallow waters by causing calcium carbonate (C_aCO_3) shells, and their associated organic carbon (ballast carbon), to dissolve higher up in the water column. This is potentially one of the most important positive ocean feedback mechanisms for enhancing the return of CO_2 back to the atmosphere.

Question 5. It is essential to start a global research and monitoring program for ocean acidification. We should be utilizing the observing systems already in place including the undersea research program. What are your recommendations for utilizing the current infrastructure of ocean observing systems and satellites to monitor ocean acidification?

Answer. As technology develops, our current ocean observation infrastructure may be enhanced by including additional specific sensors to monitor ocean acidification. For example, NOAA scientists and partners recently launched the first operational buoy with a new sensor to monitor ocean acidification in the Gulf of Alaska. This is the first system specifically designed to monitor ocean acidification, and is a new tool for researchers to examine how ocean circulation and ecosystems interact to determine how much carbon dioxide the North Pacific Ocean absorbs each year. The addition of similar carbon system sensors onto current observation platforms, such as the OceanSites moored arrays (funded by NOAA and the National Science Foundation and Coral Reef Metabolic Monitoring Network) could provide an excellent foundation for a global monitoring program to monitor ocean acidification in the Atlantic and Pacific and to validate models of future changes.

Question 5a. What information can be gained from monitoring natural variations over a long time period of time and in several different oceanic regions?

Answer. These data sets provide information on long-term natural and anthropogenic variability of the carbon system in the oceans. They are critical for understanding the future impacts on biological systems via ocean acidification.

Question 6. This year I requested funding through the Appropriations Subcommittee on Commerce, Justice, Science to fund the National Research Council report on ocean acidification mandated by Magnuson-Stevens Fishery Conservation and Management Reauthorization Act. Has NOAA yet identified the compelling research needs for this study?

Answer. Yes, NOAA has identified key issues associated with ocean acidification and fisheries, and how the National Academy of Science's Ocean Studies Board can help prioritize future research and monitoring to address this significant issue. NOAA and other agencies must collaborate to design appropriate field and laboratory studies that will allow more precise forecasts of the impacts of ocean acidification on fisheries and the ecosystems that support them.

Question 6a. If so, what are the research needs for this report?

Answer. NOAA believes that the National Academy can provide an important bridge between the academic community and Federal agencies in designing and implementing appropriate long-term monitoring studies and experiments to determine how fisheries species and ecosystems may respond to acidifying oceans. The National Academy study, to be conducted through its Ocean Studies Board (OSB), will be used to help design long-term studies to monitor pH changes in vulnerable marine ecosystems of the United States, and as a method to collaborate internationally. The OSB will determine the methods, frequency and placement of monitoring sensors and oceanographic sensing to track ocean acidification over time, and in relation to changes in atmospheric CO_2.

Currently about 51 percent of the value of United States fisheries landings is made up of bivalve mollusks and crustaceans. As these species contain high levels of calcium carbonate as shell material, they are thought to be particularly vulnerable to ocean acidification. Ocean plankton, the base of shallow-water marine food chains, include species that also incorporate calcium carbonate into their shells and are thus likely to be influenced by acidification. Other species, contributing about 5 percent of the value of U.S. fisheries, occur in shallow water tropical coral ecosystems that are highly sensitive to pH variations and temperature changes. Finally, deep-sea coral ecosystems are also likely to be impacted by ocean acidification and these species are now regulated under the newly re-authorized Magnuson-Stevens Fishery Conservation and Management Act. The National Academy study will determine which of these biological communities are most at risk, and will design appropriate field and laboratory studies of the physiological responses of these organisms to ocean acidification.

In addition to the National Academy study, which will focus on monitoring and research strategies and priorities for the U.S., NOAA will also coordinate international ocean acidification science with the International Council for the Exploration of the Sea and the Pacific Marine Science Organization. These two groups, in particular, coordinate marine science among countries in the North Atlantic and North Pacific, and can assure that U.S. research priorities integrate with research conducted by other nations.

Question 7. About one-third of all man-made carbon dioxide emissions are absorbed into the ocean. However, at a certain point the oceans may no longer be able to absorb carbon dioxide at the same rate. If this happens, warming of the atmosphere will increase even more rapidly. Are we close to seeing the rate that the oceans absorb carbon dioxide slow down to a point that our global temperatures increase even faster?

Answer. The uptake of anthropogenic CO_2 is controlled by the carbon chemistry at the surface and the rate at which surface waters, laden with anthropogenic CO_2, are moved into the ocean interior and replaced with deeper waters that have not been exposed to higher atmospheric CO_2 concentrations. The rate at which the surface waters can take up CO_2 depends on the difference in CO_2 concentration in the air and sea surface, and the amount of CO_2 that is converted to other ionic species (such as bicarbonate (HCO_3), carbonate ($CO_3{}^{2-}$), and carbonic acid ($H_2CO_3{}^{-}$) in seawater. As CO_2 concentrations in the ocean increase, the percentage of CO_2 that is converted to these other ionic species decreases, and the water becomes less efficient at taking up CO_2. This is already happening—the surface water of the oceans has already become less efficient at taking up CO_2. However, even with the ocean's decreased efficiency with regard to taking up CO_2, the exponential increase in atmospheric CO_2 concentration up to this point has made it such that today's oceans take up more CO_2 each year than they have in the past. That being said, there are many things that can change this situation because the rate at which the ocean absorbs CO_2 is a balance between a number of processes. For example, if the rate at which CO_2 is moved from the surface ocean into the interior ocean slows because of changes in thermohaline circulation, then the rate of CO_2 absorption will also decrease. If the rate at which CO_2 is rising into the atmosphere slows, then the ocean uptake rate will also decrease. Predicting when and how these processes, and others not listed here, will change is difficult. According to Chapter 5 of the 4th Assessment Report by the International Panel on Climate Change Working Group I, the fraction of the net CO_2 emissions taken up by the ocean (the uptake fraction) was 37 percent ±7 percent during the period from 1980 to 2005, compared to 42 percent ±7 percent during the 1750 to 1994 period. The errors in this estimate are still too large to determine if these rates are different.

Question 7a. How does temperature affect the rate at which ocean acidification occurs?

Answer. CO_2 is less soluble in warm water, so as the oceans warm they will become less efficient at taking up CO_2 from the atmosphere. In addition, as you warm a body of water but keep the total amount of dissolved carbon the same or greater, then the proportion of carbonic acid (H_2CO_3, the acidic form of carbon dioxide) in the water will increase, and the pH of the warmer water will therefore be lower. Thus, rising ocean temperatures will tend to accelerate ocean acidification.

However, temperature's impact on the rate at which ocean acidification occurs is small relative to the impact of rising atmospheric CO_2 levels. As CO_2 concentration continues to increase in the atmosphere, the ocean will continue to take up larger quantities of CO_2, thereby exacerbating ocean acidification.

Question 7b. The Arctic Ocean is becoming warmer and fresher which may slow down thermohaline circulation. What are the implications of these changes on ocean acidification?

Answer. The Arctic Ocean is one of the oceanic regions that will experience major changes in carbonate saturation due to ocean acidification over the next 40–50 years. This is primarily due to the extremely low temperatures of the surface waters and lowered alkalinities due to the ice melting.

Question 7c. How does the increase in atmospheric carbon dioxide and subsequent warming affect atmospheric and oceanic circulation? Will the increase in atmospheric and ocean temperatures result in more frequent El Niño's and intense hurricane seasons?

Answer. The oceans and the atmosphere constitute intertwined components of Earth's climate system. Evaporation from the ocean transfers huge amounts of water vapor to the atmosphere, where it travels aloft until it cools, condenses, and eventually precipitates in the form of rain or snow. Changes in ocean circulation or water properties can disrupt this hydrological cycle on a global scale, causing flooding and long-term droughts in various regions.

Higher temperatures caused by increases in atmospheric carbon dioxide could add fresh water to the northern North Atlantic by increasing precipitation and by melting nearby sea ice, mountain glaciers, and the Greenland ice sheet. This influx of fresher and warmer water could reduce the sea surface salinity and density, leading to a slow down of the global hydrological cycle (thermohaline circulation).

According to all models used in the 4th Assessment Report by the Intergovernmental Panel on Climate Change Working Group I, the strength of the atmospheric overturning circulation decreases as the climate warms (Held and Soden, 2006; Vecchi and Soden, 2006), in a manner consistent with theoretical arguments (Betts and Ridgeway, 1989; Betts, 1998; Knutson and Manabe, 1995; Held and Sodden, 2006). The models project that this weakening should occur preferentially to the east-west overturning of air near the Equator, known as the Walker circulation. Such a weakening of the Walker circulation, in turn, would lead to a reduction in near-surface wind-driven currents in the near-equatorial oceans (Vecchi and Soden, 2007). Long-term records of atmospheric sea-level pressure indicate that weakening of the Walker circulation may already be underway, and this weakening is partially attributable to increases in greenhouse gases (Vecchi *et al.,* 2006; Zhang and Song, 2006). However, long-term changes of oceanic conditions are mixed, with some studies showing changes inconsistent with a slowing circulation (Cane *et al.,* 1997; Hansen *et al.,* 2006) and other studies showing changes more consistent with the slowing circulation (Cobb *et al.,* 2001, 2003).

The El Niño-Southern Oscillation (ENSO) system is a naturally occurring climate phenomenon that leads to major fluctuations in global climate patterns at approximately 3–7 year intervals. There is scientific debate over the influence that rising globally-averaged temperatures has had and will have on the frequency and intensity of ENSO fluctuations. What is certain is that natural fluctuations in temperature lead to warmer and cooler years than normal. If the average temperature is rising, as it has in the 20th century and is expected to in the 21st century (Guinotte *et al.,* 2003), the warm temperatures during natural oscillations periods will be even hotter than those of the past. How the mechanisms responsible for controlling the timing and intensity of El Niño's will likely change in a warming climate is still not clear (van Oldenborgh *et al.,* 2005). Therefore, it is difficult to say whether warming will result in more frequent El Niño's. We do know, however, that El Niño's have a dramatic impact on the ability of the oceans to take up CO_2, so if the frequency of ENSO events does change then it will definitely impact ocean acidification.

It is likely that some increase in tropical cyclone peak wind-speed and rainfall will occur if the climate continues to warm (IPCC, 2007). However, there is no firm conclusion on whether there is currently a global warming signal in the tropical cyclone climate record to date. Models also project that storm tracks should move poleward in a warming world (Yin, 2005), and that the northern edge of the sinking branch of the equator-subtropics overturning of air—known as the Hadley circulation—should move polewards, with an associated poleward movement of dry regions (Lu *et al.,* 2006).

Question 7d. Which ocean regions will be first to experience large changes in carbonate chemistry? How long before large changes occur?

Answer. According to the modeling studies of Orr *et al.,* (2005, 2006), the Arctic and Southern Oceans will become undersaturated with respect to aragonite in the second half of this century. During this period, the Southern Ocean's aragonite saturation horizon shoals from its present average depth of 730m all the way to the surface. Similar large migrations of the aragonite saturation horizon are projected for the North Atlantic. In the North Pacific, portions of the subarctic Pacific will undergo undersaturation (with respect to aragonite) by the end of the century. In the Orr *et al.* (2005) modeling study, the concentration of carbonate ions that corals use to build their skeletons (the reef) will become inadequate to support reefs around the middle of the century.

Question 8. How will lower calcification rates, due to an increase in ocean acidification, higher ocean temperatures, and changes in nutrients affect ocean carbon chemistry and carbon export rates?

Answer. As indicated in the answer to Question 4b above, the Buesseler *et al.* (2007) article points to the need for more research on the nature and rates of organic matter remineralization and carbon export processes in the upper water column. We do not know if ocean acidification will enhance the process of remineralization in shallow waters by causing calcium carbonate shells, and their associated organic carbon (ballast carbon), to dissolve higher up in the water column. This is potentially an important positive ocean feedback mechanism for enhancing the return of CO_2 back to the atmosphere.

Question 9. What are the expected changes to the biological pump—the process which transports carbon throughout the ocean—due to the increase in carbon dioxide and what will be the consequences of these changes?

Answer. Calcium carbonate particles play a significant role in the transport of organic matter to the deep ocean by acting as a ballast mineral particle, absorbing organic matter at shallow depths and carrying it downward as the particles settle to deeper depths and dissolve.

Calcium carbonate dissolution at increasingly shallower depths in the oceans could possibly decrease the depth of remineralization of organic matter, causing a reduction in the ocean uptake of CO_2. This process needs to be quantitatively assessed for changing pH conditions in the oceans.

Question 10. Fossil-fuel use is also increasing the amounts of nitric and sulfuric acid deposition in the oceans. How will these elements alter surface seawater alkalinity and pH?

Answer. Anthropogenic nitrogen and sulfur deposition to the ocean surface alter surface seawater chemistry, leading to acidification and reduced total alkalinity. The acidification effects, though not as large globally as those of anthropogenic CO_2 uptake, could be significant in coastal ocean regions.

Question 10a. Will the impacts of these elements differ in coastal waters versus open ocean and how may they affect marine ecosystems?

Answer. According to a recent paper by Doney *et al.* (in press, *Proceedings of the National Academy of Science,* 2007), the deposition of anthropogenic nitrogen and sulfur has a relatively small effect on changes in open-ocean surface water chemistry, relative to the effect of CO_2 increases due to the oceanic uptake of anthropogenic CO_2. However, the impacts of nitrogen and sulfur are more substantial in coastal waters, where the ecosystem responses to ocean acidification could have severe implications for coastal inhabitants.

Question 11. During the hearing a question was raised regarding the global average increase in ocean temperature of 0.04° C. It is well known that the largest increases in ocean temperature are in the surface waters and this plays a large role in the Earth's heat budget. Can you please explain how significant the warming has been in the surface waters and what the implications have been for increased sea surface temperature as it relates to hurricane intensity, El Niño, drought, and other extreme weather events?

Answer. Based on historic and paleoclimatic records, the global mean land and ocean surface temperature has increased by 0.8±0.2° C (1.4±0.3° F) since the last half of the nineteenth century, and global mean surface temperatures increased at a rate of about 0.2° C/decade over the last few decades. Present temperatures are the warmest on record going back through at least the last 1,000 years, and we will likely soon be experiencing temperatures warmer than at any time in the last million years (Hansen *et al.,* 2006). Subsurface ocean temperatures down to 3,000 m (10,000 feet) depth are also on the rise. More than 80 percent of the added heat resides in the ocean. The impacts of the increased heat content are described below.

- Hurricane Intensity: It is likely that some increase in tropical cyclone peak wind-speed and rainfall will occur if the climate continues to warm; however, there is no firm conclusion on whether there is currently a global warming signal in the tropical cyclone climate record to date.
- El Niño: The El Niño-Southern Oscillation (ENSO) system is a naturally occurring climate phenomenon that leads to major fluctuations in global climate patterns at approximately 3–7 year intervals. There is scientific debate over the influence that rising globally-averaged temperatures has had and will have on the frequency and intensity of ENSO fluctuations. What is certain is that natural fluctuations in temperature lead to warmer and cooler years than normal. If the average temperature is rising, as it has in the 20th century and is expected to in the 21st century, the warm temperatures during natural oscillations periods will be even hotter than those of the past.
- Drought: Droughts have increased, consistent with acceleration in the water cycle and greater evaporation and transport of water vapor at the scale of continents. Observed changes in sea surface temperatures, circulation patterns and decreased snowpack and snow cover are also linked to drought.

Question 11a. Can you highlight different regions that have experienced large increases in surface water temperature and how much the surface waters have warmed?

Answer. According to the 4th Assessment Report by the Intergovernmental Panel on Climate Change (IPCC) Working Group I, the oceans are warming. Recent warming is strongly evident at all latitudes in sea surface temperatures (SST) over each of the oceans: there are inter-hemispheric differences in warming in the Atlantic; the Pacific is punctuated by El Niño events (discussed in detail in answer to question above) and Pacific decadal variability that is more symmetric around the equator; while the Indian ocean exhibits steadier warming throughout. These characteristics lead to important differences in regional rates of surface ocean warming, and understanding of the variability and trends in different oceans is still developing. A full discussion of observations and oceanic climate change and sea level is included in Chapters 3 and 5 of the IPCC Working Group I report.

Estimating regional SST increases is more difficult than estimating global ocean temperature increases, due to uncertainties in how missing data points are dealt with and in correcting for systematic errors in measurements. These uncertainties are all amplified at the smaller scale (*e.g.,* regional vs. global) and the further we go back in time.

Given the uncertainties indicated above, following is a list of linear trends in SST in the tropics, computed over the period 1880–2006, in units of °C per 100 years—to get the total rise of the linear trend, multiply by 1.27:

- Averaged across the tropics, sea surface temperatures have increased at a rate of 0.35–0.45° C per 100 years since the 1880s.
- The largest tropical warming in the 20th century has occurred in the northern Indian Ocean (0.46–0.73° C per 100 years) and the southern tropical Atlantic (0.56 − 0.77° C per 100 years) since 1880.
- For the northern tropical Atlantic, the range is between 0.24–0.52° C per 100 years since 1880.
- In the tropics, the greatest uncertainty in temperature trend is in the eastern equatorial Pacific, where sparse data and strong natural year-to-year fluctuations associated with El Niño/La Niña make estimating the long-term trend more problematic than in other regions, the observationally-based estimates range from 0.12–0.5° C per 100 year since 1880.

These trends are based on the Kaplan *et al.,* (1998), Rayner *et al.,* (2003), and Smith and Reynolds (2004) SST datasets, and are computed over the period 1880–2006. The exact regions used to calculate these trends:

- Tropics: Global, 30° S–30° N.
- Northern Indian Ocean: 50° E–100° E, 0° N–20° N.
- South Atlantic: 40° W–10° E, 20° S–0° N.

- North Atlantic: 80° W–30° W, 5° N–20° N.
- Eastern Equatorial Pacific: 150° W–90° W, 5° S–5° N.

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RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. DANIEL K. INOUYE TO DR. LARA J. HANSEN

Question 1. Coral reefs are not just critical habitat for fish. In my state of Hawaii, they are also an economic engine supporting both fishing and tourism. Is ocean acidification or the increase in sea temperature the more pressing issue for protecting and preserving Hawaii's coral reefs and other marine resources and why?

Answer. You can not prioritize one of these issues over the other. They share the same root cause and will both dramatically affect our Nation's coral reefs. Increasing atmospheric CO_2 is increasing global temperatures, including the ocean's temperatures. This same CO_2 is being absorbed by our oceans and lowering their pH. They are inextricably linked; prevent one and you prevent both, and if you fail to prevent either it will result in an increase in global as well as ocean temperatures. Unfortunately, we are already seeing the manifestation of both. It is possible that ocean acidification is the more ominous as we do not know all of the effects it will have, owing to our long believe that the ocean's vast buffering capacity prevents such things in our timeframe. It exacerbates the ongoing adverse effects we have been seeing due to increasing water temperature for the past several decades. We must do everything we can to limit both.

Question 2. How can we incorporate actions to address these issues into an overall management strategy for protecting Hawaii's corals and other marine resources?

Answer. There are four general steps that WWF feels are crucial to improving management in the face of climate change. First, you must assess where your resources are and ensure that those which are naturally more resilient are protected. Where possible you manage along climatological gradients so that these ecosystems can respond accordingly. Second, you must limit all of the non-climate stresses to levels where climate change's added stress does not exacerbate them, or vice versa. This includes further reducing acceptable levels of habitat loss and fragmentation, pollutants, invasive species, disease/pests, and over- or destructive harvest. Third, we need to start implementing these approaches as soon as possible, in a do-no-harm manner, start monitoring them, adjust as necessary and share lessons widely. Fourth, we *must* reduce the rate and extent of climate change. This means to rapidly reduce greenhouse gas emissions.

Question 3. Dr. Hansen, could you tell me what adaptation and mitigation steps you think the United States needs to take to address the threats that climate change and ocean acidification pose to our ocean resources?

Answer. First and foremost we need to get serious about reducing greenhouse gas emissions. Nothing we have done to date gets close to what we must do to save our national and global economy, natural resources, biodiversity and well-being. We need to do this as quickly as possible. This means taking action to improve conservation of energy (fuel economy, reduced use of long-distance transmission of electricity, real standards on appliances), switch to renewable energies that produce no greenhouse gases and finally, decommission those sources of power generation that do.

Second, we need to recognize that we are already committed to a certain level of climate change, likely about 2 degrees Celsius (I believe that even this is too much). We must also recognize that this will have serious impacts on our oceans, our citizens, our forests, our freshwater systems, our highway systems, our wastewater treatment facilities, and our agricultural system. We need to rethink every piece of legislation, and assess whether or not it is prepared for climate change. Are we making bad investments because they are vulnerable to the effects of climate change? We need to think proactively now because the climate is changing rapidly. There is a book about the Arctic climate experience called "The World is Faster Now". It is and we must be prepared.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. MARIA CANTWELL TO DR. LARA J. HANSEN

Question 1. The most rigorous mitigation goal in the recent summary report by the Intergovernmental Panel on Climate Change is to stabilize atmospheric greenhouse gas levels between 445 and 710 parts per million by 2030. But given that the current concentrations of atmospheric carbon are estimated at 379 parts per million, shouldn't this target be set at a much lower level if we are to effectively address climate change? What is the expected temperature increase of this range?

Answer. 2.0 to 4.0° C

Question 1a. What would be the impacts on our ocean resources if we were to reach these emissions levels?

Answer. Allowing emissions levels to reach the upper end of this range is still unfathomable. For the past 650,000 years we have stayed between about 180 and 300 ppm. To now be at 384 ppm and say we are headed to 710 should be seen by this planet's inhabitants as unacceptable. That amount of warming would mean unprecedented coral bleaching, loss of many, if not most coral species, altered marine food webs as species shift their ranges or simply disappear (imagine if you will what the loss of krill, the base of the marine food web, would mean for life on Earth?), changes in the dominant phytoplankton species (these are what produce most of our oxygen), loss of most of the world's terrestrial ice causing massive sea level rise, altered ocean currents and even more heating as the planet becomes less reflective. All of these changes will cause unprecedented responses in human communities, such as movement of climate refuges, famine, and disease. In all honesty, this level of warming is not something that ecologists like to ponder; it may be one of the most cataclysmic scenarios that I can ponder.

Question 1b. Do you think that policymakers should specifically take ocean impacts into account when setting emissions reductions targets?

Answer. Absolutely. The oceans provide myriad services that we take for granted but they sustain life on this planet. We must also recognize that the more CO_2 we put in the atmosphere, the greater the ocean acidification commitment, which is something that we do not fully understand the consequences of.

Question 1c. Do current emissions reduction targets sufficiently consider ocean impacts?

Answer. Most certainly not.

Question 1d. How do you think policymakers should incorporate ocean impact concerns when setting emissions reduction targets?

Answer. Yes, please see above.

Question 2. Dr. Hansen, I understand that you were part of a team that produced NOAA's publication titled "A Reef Managers Guide To Coral Bleaching". This handbook acknowledges that climate change is outside of the immediate control of most managers, and recommends that the best management strategy is often to reduce stressors that are within local control—such as reducing pollution or overfishing. What can managers facing ocean acidification learn from this approach? What are some concrete steps in the short-term and long-term that can be taken to adapt to these impacts?

Answer. Perhaps the most daunting challenge is to develop adaptation strategies in response to ocean acidification. It ranks up there with how to protect sea ice dependent creatures in a world without ice. The only short-term strategy that my team has developed is working to limit all of the other stresses so that systems can try to keep up with this change without it being exacerbated by other challenges. Unfortunately one of the key stresses that can aggravate this is warming waters. The same actions that cause acidification cause warming.

Question 2a. Aside from reducing emissions, what other steps should policymakers be taking to address the impact of climate change and ocean acidification on the oceans?

Answer. We should start doing everything we can to make ocean systems more robust, by reducing all of the other insults we have sent their way. But really, the only solution, the only lifeline for the oceans, is for us to stop dumping CO_2 in them, which is exactly what we do when we dump it into the atmosphere.

Question 3. What are the potential impacts of some of the currently proposed climate change mitigation strategies on the marine environment—such as iron stimulated plankton blooms or injection of CO_2 into sea sediments?

Answer. Storing CO_2 in the world's oceans, either through direct injection or stimulating phytoplankton assimilation is risky business. You are trading one environmental disaster for another. There may be some merit to storing carbon in old oil and gas deposits since they are presumably not environmentally sensitive locations, but this is not true of the ocean. In the case of injection, you are damaging the deep ocean communities which are very sensitive to such changes in pH and gas composition as they are extremely stable systems (very little variability in any physical parameters). You are also acidifying the oceans from the bottom up, rather than the top down. In the case of ocean "fertilization" you are increasing ocean productivity, which can have negative consequences as well as the desired. You will change the species composition of the phytoplankton community, selecting for species that are iron limited. These phytoplankton, in their current composition, provide many ecosystem services. Will the new set do so as well? We don't know.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. DANIEL K. INOUYE TO JAMES D. WATKINS

Question 1. Admiral Watkins, what are the most important steps that the United States should take to address the threats we are learning about today, in terms of research and monitoring, outreach and education, and adaptation and mitigation measures? Can you identify some specific actions that Congress should take to strengthen Federal efforts in the area of ocean impacts of climate change?

Answer. This reply is to questions 1 and 3 from Chairman Inouye. Earlier this summer JOCI consulted with leading experts in ocean and climate change science and policy regarding the development of recommendation for incorporating oceans as part of climate change legislation under consideration by Congress. The Initiative suggests that Congress address the link between oceans and climate change by addressing needs in two key areas: governance reform and science. Clearly, additional funding will be necessary to make sustained progress in both areas. A more detailed discussion of our recommendations is included in the *attached* paper, which was sent to leaders in the House and Senate, as well as the Administration. I request that the entire text of the paper be included as part of my reply to the Committee's follow-up questions.

Below is brief summary of the key recommendations from the paper.

Governance Reform

Climate change involves complex and dynamic interactions of the atmosphere, ocean, land, their related ecosystems, and human activities. The complexity and breadth of issues associated with efforts to understand, mitigate, and adapt to climate change, the scale of its impacts from the local to the global level, and the need to understand the relationship between natural variability and climate change, make it essential that the Nation have a coherent and comprehensive strategy to address this new challenge. This will require the establishment of a Climate Change Response Office to guide the development and implementation of a National Climate Change Response Strategy.

Ocean science and management must be recognized as key elements of such a national response strategy. Actions that would help ensure this occur include codifying the White House Committee on Ocean Policy and charging it with supporting a broader National Climate Change Response Strategy. Another beneficial step would be to codify and strengthen the National Oceanic and Atmospheric Administration (NOAA), which is the key Federal agency providing climate-related services and ocean management information. Finally, Congress should require a biennial integrated assessment of the Nation's progress toward mitigating and adapting to climate change impacts. An integrated assessment evaluating the collective effort of Federal programs and activities will provide a baseline from which to measure progress and will help ensure the Nation is maximizing the use of available data and information to improve the caliber of forecasts and to evaluate the effectiveness of management actions.

1. Charge the National Academy with recommending a process and strategy to respond to climate change, including consideration of the organization and functions of a National Climate Change Response Office responsible for guiding Federal programmatic and budgetary climate change activities.
2. Codify and strengthen the White House Committee on Ocean Policy, and give it a key role in supporting the activities of the Climate Change Response Office.
3. Codify and strengthen the National Oceanic and Atmospheric Administration (NOAA), realigning the agency's organizational structure to enhance and focus its capacity to provide climate-related services and improve ocean and coastal management.
4. Require a biennial integrated assessment of the Nation's progress toward meeting its objectives to mitigate and adapt to impacts associated with climate change and variability.
5. Require the submission of an integrated budget to consolidate and highlight priorities established by the National Climate Change Response Office that would accompany the President's annual budget request.

Science Requirements

Credible and timely scientific information will be essential as the Nation begins the process of responding to the challenges associated with climate change. A much more comprehensive and robust science enterprise that incorporates a better understanding of the ocean's role in climate change is required to forecast more accurately the magnitude and intensity of this change at multiple scales, as well as to evaluate options for mitigation and adaptation. Unfortunately, the existing ocean and coastal science enterprise supporting climate change research, observations, data management, and socioeconomic analysis is limited.

The status of infrastructure supporting ocean science, such as ship, satellites, buoys, cabled observatories, planes, and other monitoring hardware, is bleak. Additionally, support for shore-side lab work, where data for the observing systems is analyzed, quality-controlled, synthesized, and integrated, has eroded. Further underlying these weaknesses is a lack of capability to transmit large amounts of ocean data in real time and a disjointed data management system that prevents scientists from fully utilizing the data that are being collected now.

Congress can begin to remedy this situation by calling on the administration to prioritize and request full funding to implement its Ocean Research Priorities Plan and Implementation Strategy (ORPPIS). ORPPIS provides a solid blueprint to guide research on the ocean's role in climate. It is the first comprehensive research strategy developed by the Administration with input from the ocean community and should be used by Congress to guide its ocean science funding priorities.

Congress should also authorize and fund the implementation of an Integrated Ocean Observing System (IOOS), with the system being driven by a cooperative interagency process that incorporates expertise from outside the Federal system. Sustained research and operational monitoring and analyses programs supported by enhanced data collection, management, and synthesis capabilities are the foundation of an observation system that can refine climate change models and reduce the level of uncertainty associated with their projections.

Finally, Congress should support research and science programs focused on analyzing the potential impact various greenhouse gas mitigation strategies may have on ocean and coastal processes and ecosystem health. Recommendations for carbon sequestration in the oceans will require particularly careful review, given our growing concern about the sensitivity of marine ecosystems to changes in the biogeochemistry of ocean waters as a result of increased absorption of carbon dioxide, in particular ocean acidification.

1. Request prioritization of and provide funding to implement the Administration's Ocean Research Priorities Plan and Implementation Strategy, with a focus on developing a science enterprise that is responsive to societal and environmental concerns.

2. Enact legislation authorizing the implementation of an Integrated Ocean Observing System, incorporating both coastal and global components.

3. Fund major ocean observation research and monitoring infrastructure systems and supporting science and data management programs, such as an Integrated Ocean Observing System, the Ocean Observatories Initiative, research vessels, and remote sensing programs.

4. Enhance funding support for transitioning ocean and atmospheric data collection and synthesis programs from research to operational status, with ongoing engagement of the ocean science community in the operation, evaluation, and evolution of the programs.

5. Support research to evaluate the impact of greenhouse gas mitigation policies on coastal and ocean processes and ecosystem health (*e.g.,* oceanic carbon sequestration, biofuel production).

Question 2. Do you believe that the current Federal budget to address the ocean impacts of climate change is sufficient?

Answer. Clearly, the answer is no, as I responded when Senator Stevens asked a similar questions during the hearing. The short- and long-term implications of climate change are significant in relationship to the impact on the environmental health of marine ecosystems and the economic vitality of coastal communities. In the recent Joint Initiative report to Congress, "From Sea to Shining Sea," we identify $750 million in high priority funding needs to support the recommendations of the two Commissions. Much of the funding identified in this report would directly contribute to improving our understanding of the oceans role in climate processes, as well as strengthen coastal community's capacity to adapt to the changes accompanying these shifts. For example, we support enhancing ocean governance and coastal management, such as improving interagency collaboration, expanding regional coordination, and strengthening programs that focus on system-wide watershed activities, such as the Coastal Zone Management Program and USDA and U.S. Army Corps of Engineer programs.

In the science realm we call for oceans to be incorporated into the President's American Competitiveness Initiative, for the expansion of ocean research and exploration initiatives, and building a strong Integrated Ocean Observing System to monitor, observe, map, and analyze changes in our oceans, coasts, and Great Lakes. A final area that demands attention, but always seems to be ignored, is support of education and outreach, for without an informed public there will be a lack of political will and scientific expertise to move us toward more sustainable management strategies. Again, I would refer Members of the Committee and Committee staff to our "From Sea to Shining Sea" report for more detailed funding recommendations.

ATTACHMENT

Addressing Oceans and Climate Change in Federal Legislation

July 2007

Introduction

The purpose of this paper is to provide Congress with information and recommendations to support the enactment of legislation that incorporates ocean science, management, and education into a national initiative to mitigate and adapt to climate change. This initiative must complement ongoing efforts to understand, monitor, and forecast changes associated with natural variability, such as El Niño and the Pacific Decadal Oscillation, since anthropogenic climate change will also impact the frequency, pattern, and severity of these natural processes. The goal is to improve our collective understanding of the role of the oceans in climate change in order to inform policies and strategies intended to reduce the vulnerability of and increase the resiliency of our economic and ecological systems to impacts associated with climate change. It is the Joint Ocean Commission Initiative's view that this goal can best be met through a broad national climate change response strategy that includes an emphasis on the oceans role in climate-related processes.

After consultation with leading experts in ocean and climate change science and policy, the Joint Ocean Commission Initiative suggests that Congress address the link between oceans and climate change by addressing needs in two key areas: governance reform and science. Clearly, additional funding will be necessary to make sustained progress in both areas. The actions recommended by the Joint Ocean Commission Initiative are summarized below and discussed in more detail in the pages that follow.

Governance Reform

1. Charge the National Academy with recommending a process and strategy to respond to climate change, including consideration of the organization and functions of a National Climate Change *Response* Office responsible for guiding Federal programmatic and budgetary climate change activities.
2. Codify and strengthen the White House Committee on Ocean Policy, and give it a key role in supporting the activities of the Climate Change Response Office.
3. Codify and strengthen the National Oceanic and Atmospheric Administration (NOAA), realigning the agency's organizational structure to enhance and focus its capacity to provide climate-related services and improve ocean and coastal management.
4. Require a biennial *integrated* assessment of the Nation's progress toward meeting its objectives to mitigate and adapt to impacts associated with climate change and variability.
5. Require the submission of an integrated budget to consolidate and highlight priorities established by the National Climate Change Response Office that would accompany the President's annual budget request.

Science Requirements

1. Request prioritization of and provide funding to implement the Administration's *Ocean Research Priorities Plan and Implementation Strategy,* with a focus on developing a science enterprise that is responsive to societal and environmental concerns.
2. Enact legislation authorizing the implementation of an Integrated Ocean Observing System, incorporating both coastal and global components.
3. Fund major ocean observation research and monitoring infrastructure systems and supporting science and data management programs, such as an Integrated Ocean Observing System, the Ocean Observatories Initiative, research vessels, and remote sensing programs.
4. Enhance funding support for transitioning ocean and atmospheric data collection and synthesis programs from research to operational status, with ongoing engagement of the ocean science community in the operation, evaluation, and evolution of the programs.
5. Support research to evaluate the impact of greenhouse gas mitigation policies on coastal and ocean processes and ecosystem health (*e.g.,* oceanic carbon sequestration, biofuel production).

The Role of Oceans in Climate Change

Increasing awareness and concerns about climate change have elevated the urgency to take action to mitigate its causes and make preparations to adapt to its anticipated economic and environmental impacts. At continental, regional, and ocean basin scales, numerous long-term changes in climate have been observed. These include changes in arctic temperatures and ice, as well as widespread changes in, ocean salinity, wind patterns, the quantity of precipitation, and various aspects of extreme weather.[1] As Congress moves forward in developing climate change policies, the accompanying legislation should recognize the fundamental role oceans play in governing climate change and Earth-related processes. Some important facts regarding the relationship between oceans and climate change include the following:

[1] Intergovernmental Panel on Climate Change. 2007. Report of Working Group I *The Physical Science Basis.*

- Oceans cover 71 percent of the Earth's surface and average over 12,200 feet in depth.
- Water holds approximately 1,000 times the amount of heat as air, and the interaction between ocean circulation and the global distribution of heat is the primary driver of climatic patterns.
- The oceans are warming, particularly since 1950s, with global mean sea surface temperature having increased roughly one degree Fahrenheit in the 20th century.[2]
- Sea levels rose 7 inches during the 20th century and nearly 1.5 inches between 1993 and 2003 alone.[2]
- Oceans are a major carbon sink and have absorbed fully half of all fossil carbon released to the atmosphere since the beginning of the Industrial Revolution.[2]
- The absorption of carbon has resulted in increasing ocean acidification, impacting the health of marine ecosystems and species, including, but not limited to, those with carbonate-based skeletons (*e.g.,* corals), as well as influencing the important role ocean plays in the global cycling of carbon.
- Little to no Arctic sea ice is expected in the summers by 2100.[2]

Governance Reform to Address Oceans and Climate Change

Climate change involves complex and dynamic interactions of the atmosphere, ocean, land, their related ecosystems, and human activities. The complexity and breadth of issues associated with efforts to understand, mitigate, and adapt to climate change, the scale of its impacts from the local to the global level, and the need to understand the relationship between natural variability and climate change make it essential that the Nation have a coherent and comprehensive strategy to address this new challenge.

Unfortunately, there is general agreement in the scientific community that the current Federal climate change governance regime is too limited in scope and must be expanded if it is to be truly comprehensive. A Climate Change *Response* Office is required to guide the development and implementation of a National Climate Change Response Strategy. Such an office must have the authority to direct the activities of multiple Federal agencies and have a strong role in the budget formulation process. This will require designing and implementing a strategy that balances the need to conduct basic and applied research, monitoring and analysis, and modeling and forecasting, with the goal of translating data into information products that can be used to develop sound policies to mitigate and adapt to environmental and socioeconomic impacts stemming from climate change.

Ocean science and management must be recognized as key elements of a national response strategy. Thus, the existing interagency coordination process operating under the White House Committee on Ocean Policy[3] should be codified and charged with supporting the effort to institutionalize a broader National Climate Change Response Strategy. An additional action needed to strengthen the Federal Government's capacity to respond to climate change is to codify and strengthen the National Oceanic and Atmospheric Administration (NOAA). As a key provider of climate-related services and ocean management information, and as one of the principle agencies investigating the ocean's role in climate variability, NOAA plays a lead role in matters related to climate change. However, an outdated organizational structure and the lack of resources have limited NOAA's ability to fulfill its multiple mandates. The opportunity is ripe for Congress to reevaluate NOAA's organizational structure and realign programs along its core functions: environmental assessment, prediction, and operations; scientific research and education; and marine resource and area management. Strengthening NOAA and realigning its functions would greatly enhance its capacity to provide climate-related services and facilitate the implementation of proactive management measures to mitigate anticipated impacts on coastal economies and ecosystems.

Finally, Congress should require a biennial integrated assessment of the Nation's progress toward mitigating and adapting to climate change impacts. An integrated assessment evaluating the collective effort of Federal programs and activities will provide a baseline from which to measure progress and will help ensure the Nation is maximizing the use of available data and information to improve the caliber of forecasts and to evaluate the effectiveness of management actions. An additional step that would facilitate better integration of Federal programs would be a requirement for the submission of an integrated budget that clearly identifies priorities es-

[2] Doney, Scott. 2006. *The Dangers of Ocean Acidification.* Scientific American (March).
[3] Executive Order 13366, 2004.

tablished by the proposed National Climate Change Response Office and how those priorities relate to and complement efforts directed at understanding the ocean's role in climate change. Congressional oversight of the Federal budget is its most powerful tool, but Congress' capacity to help guide a response to an issue as complex as climate change is compromised when information is dispersed throughout the President's budget.

Ocean and Coastal Science Requirements

Credible and timely scientific information will be essential as the Nation begins the process of responding to the challenges associated with climate change. Better science, when linked with improved risk management and adaptive management strategies, will help guide a process that must deal with the relatively high levels of uncertainty related to mitigation alternatives and the range of impacts associated with climate change and variability. A much more comprehensive and robust science enterprise that incorporates a better understanding of the ocean's role in climate change is required to forecast more accurately the magnitude and intensity of this change at multiple scales, as well as to evaluate options for mitigation and adaptation. This process must also include strengthening capacity in the social sciences, whose contributions will influence risk and adaptive management strategies significantly given the immense economic impact climate change will have on coastal communities.

Unfortunately, the existing ocean and coastal science enterprise supporting climate change research, observations, data management, and socioeconomic analysis is limited. Despite the unprecedented opportunities to capitalize on technological advances, future capacity is compromised due to a lack of fiscal support for key infrastructure and science programs. For example, the U.S. commitment to constructing an observing system focused on studying physical ocean processes is only half complete, while satellite systems responsible for generating invaluable data across large areas of oceans are aging. The construction of replacement systems are behind schedule, over budget, and as currently configured, may have less capacity than the systems they are replacing. The status of infrastructure supporting on and underwater ocean science, such as ship, buoys, cabled observatories, planes, and other underwater monitoring hardware, is bleak. Additionally, support for shore-side lab work, where data for the observing systems is analyzed, quality-controlled, synthesized, and integrated, has eroded. Further underlying these weaknesses is a lack of capability to transmit large amounts of ocean data in real-time and a disjointed data management system that prevents scientists from fully utilizing the data that are being collected now. Stagnant funding supports only bare-bones research, monitoring, modeling, and analysis enterprises that have difficulty providing the quantity and quality of data needed to generate information with the relatively high levels of confidence demanded by decisionmakers facing difficult policy choices.

Congress can begin to remedy this situation by taking the following series of steps. First, it should call on the administration to prioritize and request full funding to implement its *Ocean Research Priorities Plan and Implementation Strategy* (ORPPIS). ORPPIS provides a solid blueprint to guide research on the ocean's role in climate, including the development of a comprehensive observing system and other ocean-related research priorities that will improve our ability to enhance the resiliency of marine ecosystems and coastal economies to climate-induced changes. Particularly noteworthy in ORPPIS is its emphasis on using improved understanding to provide better and timelier policy and resource management decisions, relying on much stronger support for social and economic research. It is the first comprehensive research strategy developed by the Administration with input from the ocean community and should be used by Congress to guide its ocean science funding priorities.

Congress should also authorize and fund the implementation of an Integrated Ocean Observing System (IOOS). Support for the implementation of the coastal and global IOOS should be driven by a cooperative interagency process that incorporates expertise from outside the Federal system. Congressional support should also extend to major observing initiatives supported by the National Science Foundation, as well as to remote sensing satellite programs supported by NASA's Earth Science program. As noted earlier, the loss or diminishment of remote sensing capabilities, in addition to the lack of support for transitioning ocean and atmospheric data collection and synthesis program from research to operational status, has significantly compromised our Nation's capacity to monitor the vast expanse of the ocean. Sustained research and operational monitoring and analyses programs supported by enhanced data collection, management, and synthesis capabilities are the foundation of an observation system that can refine climate change models and reduce the level of uncertainty associated with their projections.

Finally, Congress should support research and science programs focused on analyzing the potential impact various greenhouse gas mitigation strategies may have on ocean and coastal processes and ecosystem health. Recommendations for carbon sequestration in the oceans will require particularly careful review, given our growing concern about the sensitivity of marine ecosystems to changes in the biogeochemistry of ocean waters as a result of increased absorption of carbon dioxide, in particular ocean acidification. Similarly, increased biofuel production will generate additional runoff of nutrients, herbicides, and pesticides, further exacerbating pollution and nutrient enrichment problems in coastal waters.

Given their immense size, fundamental role as a driver of climate processes, and critical social and economic importance, it is imperative that Congress focus greater attention and resources on improving our understanding and management of our oceans, coasts, and Great Lakes. The actions recommended above are important steps that will lay the foundation for making great advances in ocean science and allow meaningful progress toward improved stewardship of one of nation's greatest natural resources.

RESPONSE TO WRITTEN QUESTIONS SUBMITTED BY HON. MARIA CANTWELL TO JAMES D. WATKINS

Question 1. Admiral Watkins, do you think that policymakers should specifically take ocean impacts into account when setting emissions reductions targets? Do current emissions reduction targets sufficiently consider ocean impacts? How do you think policymakers should incorporate ocean impact concerns when setting emissions reduction targets?

Answer. I cannot say how much consideration climate scientist and policymakers are giving to impacts on ocean-related chemistry and ecology as they evaluate various emission reduction scenarios. However, I strongly suspect that it is inadequate, particularly in light of the testimony presented at the hearing suggesting that atmospheric carbon dioxide levels in excess of 450 ppm may have the potential of sufficiently increasing the acidity of surface ocean water to levels that would begin to jeopardize phytoplankton productivity and the capacity of other carbonate-extracting species from forming shells and skeletons.

It is this concern and others that are driving the Joint Initiative's effort to elevate awareness of the role of oceans in climate processes. In order for policymakers to make informed and balanced decisions regarding the incorporation of ocean-related concerns in the emission reduction targeting process, they should pursue two strategies. First, they should support additional ocean science to get a better understanding of natural variability in the system, and how the accumulation of human-generated emissions are exacerbating this variability and driving other changes. Second, given the fact that acquiring this information will take some time, policymakers should strongly consider taking a precautionary approach in the target setting process. By this I mean taking a prudent, balanced approach that acknowledges the vulnerability of the ocean ecosystem to dramatic increases in carbon-based emissions, while also recognizing the multiple economic benefits and services provided by our oceans, coasts, and Great Lakes. As more information become available, the framework developed should be flexible and capable of adapting to new information. I remain very concerned about the short-sightedness of prior policies that contributed to the degradation of our oceans and coasts and strongly encourage a new strategy that incorporates full consideration of the health of our oceans and coastal communities into the decisionmaking process.

Finally, given the increased focus on identifying technologies capable of capturing carbon dioxide and other greenhouse gases; it is imperative that support for these efforts include funding to study the potential impact of storing these gases in or under our oceans. We now have a much better appreciation for the sensitive ecological balance in our oceans and must take great care not to further exacerbate existing problems by assuming our oceans are capable of further degradation.

Question 2. Admiral Watkins, how can we improve our ocean and Earth observation programs to ensure understanding of the impacts of global climate change and ocean acidification on the marine environment?

Answer. Perhaps the single most important step we can make is to implement and fully fund an Integrated Ocean Observing System (IOOS). The Joint Initiative reiterates this point in its recent climate change and oceans paper, which I reference in my response to Chairman Inouye's questions, as well as in our report to Congress, "From Sea to Shining Sea." The IOOS system, as conceived by the ocean science community, covers the spectrum of observations. This system includes a progression of activities and programs, starting with studying and understanding ongoing physical, chemical, and biological processes occurring in the oceans and along our coasts, to gain a better knowledge of how various components within the system operate and interact. The second element of the strategy includes developing and implementing systematic and sustainable observation systems, consisting of remote (satellite), *in situ* (buoys, stationary sensors), and mobile platforms (vessels, SUVs), that provide a steady accounting of changes in system processes. The third element is to use this information to refine climate and ocean models, increasing their capacity to provide credible and accurate forecasts of changes in the functioning of natural systems.

There are significant infrastructure costs associated with establishing such a system, as well as support for the synthesis and integration of the wealth of information generated by the system. However, the costs associated with this effort are minimal given the significant fiscal benefits resulting from the improved accuracy, credibility, and reliability a comprehensive earth observation system will provide. The information provided by a fully operational IOOS will be invaluable as Congress and other policymakers wrestle with difficult policy decisions that have significant socioeconomic impacts, not the least of which will be determining an appropriate target for emission reductions.

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