**WRITTEN TESTIMONY OF**
**STEVEN A. MURAWSKI, Ph.D.**
**DIRECTOR OF SCIENTIFIC PROGRAMS AND CHIEF SCIENCE ADVISOR,**
**NATIONAL MARINE FISHERIES SERVICE**
**AND ECOSYSTEM GOAL TEAM LEAD**
**NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION**
**U.S. DEPARTMENT OF COMMERCE**

**FOR AN OVERSIGHT HEARING ON**
**PROJECTED AND PAST EFFECTS OF CLIMATE CHANGE: A FOCUS ON MARINE AND TERRESTRIAL ECOSYSTEMS**

**BEFORE THE**
**COMMITTEE ON COMMERCE, SCIENCE AND TRANSPORTATION**
**SUBCOMMITTEE ON GLOBAL CLIMATE CHANGE AND IMPACTS**
**UNITED STATES SENATE**

**April 26, 2006**

## Introduction

Good afternoon, Mr. Chairman and members of the Committee. My name is Steven Murawski, and I am the Director of Scientific Programs and Chief Science Advisor at the National Marine Fisheries Service (NMFS), within the National Oceanic and Atmospheric Administration (NOAA). I also serve as leader of NOAA's Ecosystem Goal Team, which integrates the Agency's many ecological activities across its various offices. Thank you for inviting NOAA to discuss projected and past effects of climate change with a focus on marine and terrestrial ecosystems. Among NOAA's diverse missions, our tasks include understanding and predicting changes in the earth's environment and acting as the nation's principal steward of coastal and marine resources critical to our Nation's economic, social and environmental needs.

Today I will focus my remarks on how changes in climate affect marine ecosystems, particularly as they relate to NOAA's stewardship responsibilities. NOAA's work on climate change and ecosystems relevant to this hearing includes observations of the physical environment and biota, research to understand the changes in the environment and the broader ecosystem, and incorporating projected impacts of climate change into NOAA's conservation and management programs for living marine resources and ecosystems. Climate change is only one of a complex set of factors that influence marine ecosystems. It can be difficult to separate the influence of natural climate cycles, recent climate change, and other factors such as over fishing, air pollution such as sulfates, agricultural run off, land use changes resulting from land fills, drainage practices, uses of pesticides and fertilizers, development, recreational facilities and practices, inadequate storm water management, and sewage treatment. NOAA is committed to an ecosystem approach to resource management that addresses the many simultaneous pressures affecting ecosystems.

This Administration recognizes climate change as a complex and important issue and acknowledges human activities are contributing to recent observed changes in the climate system. However, scientific uncertainties still remain, including how much of the observed warming is due to human activities and how large and fast future changes will be. In 2002, the Administration created the Climate Change Science Program (CCSP; the federal interagency program focused on climate change research) to ensure the federal government's efforts and resources are used to obtain the best possible scientific knowledge as the foundation to address challenging climate change questions and support decision making. There is much important research yet to be done and CCSP – whose leadership resides in NOAA – is seeking to increase our understanding of climate change. Within CCSP there is an Ecosystem Interagency Working Group which is currently examining a variety of topics relevant to today's hearing, including: (1) the use of integrated modeling systems, observations, and process studies to project the effects of climate variability and change on near-coastal and marine ecosystems and communities; (2) combined effects of changes in land use and climate on non-point sources of pollution entering estuaries; and (3) a long-term study of the western U.S. mountains and the relationship of observed sudden ecosystem changes to changes in climate conditions.

The Climate Change Science Program is a coordinated effort across 13 agencies (U.S. Agency for International Development; Department of Agriculture; Department of Commerce, National Oceanic and Atmospheric Administration and National Institute of Standards and Technology; Department of Defense; Department of Energy; Department of Health and Human Services, National Institutes of Health; Department of State; Department of Transportation; Department of the Interior, U.S. Geological Survey; Environmental Protection Agency; National Aeronautics and Space Administration; National Science Foundation; and the Smithsonian Institution), 12 of which fund CCSP research. Funding for NOAA's CCSP initiatives are included within the NOAA Climate Program. The fiscal 2007 President's Budget request for NOAA includes spending for CCSP near-term research focus areas, including integrating new remote-sensing observations with expanded observations to build the next generation of climate prediction capabilities; development of an integrated Earth system analysis capability; integrating of water cycle observations, research and modeling; using global LANDSAT data to answer critical climate questions; an integrated North American Carbon Program; understanding the impacts of climate variability and change on ecosystem productivity and biodiversity; coping with drought through research and regional Partnerships; the International Polar Year; and an Integrated Ocean Observing System. The President's Budget restores cuts made by Congress to NOAA's Climate Program in 2006, particularly in the area of Research Supercomputing, critical to NOAA's ability to reduce some of the highest uncertainties in understanding impacts of climate variability and change. We urge the Committee to support the FY 2007 President's Budget request for NOAA.

In my testimony today I will: (a) provide information on NOAA's contributions relevant to climate change science and links to effects on marine ecosystems, (b) detail the importance of understanding climate-ecosystem links both for the affected marine areas and the human communities dependent upon them, (c) briefly describe some paleontological observations of how ecosystems have changed in response to climate variations in the past, and (d) review some contemporary observed changes in marine ecosystems thought to be related to changes in the earth's climate and issues surrounding them. Finally, I will outline some of the scientific challenges and needs for improving science to better define ecosystem impacts and inform conservation and management strategies for living marine resources taking into account climate impacts.

## NOAA's Roles in Climate and Ecosystem Sciences

Within the climate science community, NOAA is a recognized leader both nationally and internationally. Our scientists actively participate in many important national and international climate working groups and assessment activities. One of NOAA's mission goals is to "understand climate variability and change to enhance society's ability to plan and respond." NOAA is the only federal agency that provides operational climate forecasts and information services (nationally and internationally). NOAA is the leader in implementing the Global Ocean Observing System (NOAA contributes 51% of the world-wide observations to GOOS, not including satellite observations). NOAA also provides scientific leadership for the Intergovernmental Panel for Climate Change Working Group I and CCSP. To better serve the Nation, NOAA recently created a Climate Program Office (CPO) to provide enhanced services and information for better management of climate sensitive sectors, such as energy, agriculture, water, and living marine resources, through observations, analyses and predictions, and sustained user interaction. Services include assessments and predictions of climate change and variability on timescales ranging from weeks to decades.

Within the ecosystem community, NOAA's ecosystem researchers have been at the forefront of establishing links between ocean variability and impacts on marine ecosystems. NOAA has funded some research programs specifically dedicated to evaluating impacts of changes in the physical environment on marine resources. These include a program jointly undertaken with the National Science Foundation called GLOBEC (Global Ocean Ecosystem Dynamics), which just last week co-hosted a symposium on "Climate variability and ecosystem impacts on the North Pacific" with PICES (the North Pacific Marine Science Organization of which the U.S. is also a member). An exclusively NOAA program called NPCREP (North Pacific Climate Regimes and Ecosystem Productivity) seeks to improve climate-ecosystem science in the Alaskan Large Marine Ecosystem complex. Even more information on the impacts of climate on marine ecosystems is derived from NOAA's many observing programs established to aid in the management of fisheries, protected species, marine sanctuaries, corals and other specific Agency mandates.

These data, primarily collected in support of NOAA's ecosystem stewardship authorities, provide a wealth of information for interpreting climate impacts when combined with NOAA's climate, oceanographic and weather information. Results of these analyses have been widely disseminated and NOAA's contributions to the emerging science of ecosystem impacts of climate change have been significant. However, a greater understanding of the full range of climate induced impacts on ecosystems will require us to increase our observation of ecosystems in relation to variable climate forcing and focus our research on the mechanisms through which ecosystems are affected. In this way we can develop quantitative assessments and projections of climate's ecological impacts, including impacts on the resources on which human communities rely.

**Why are Links between Climate and Marine Ecosystems So Important?**

Irrespective of the ultimate causality, changes in the world's climate has resulted in changes in marine ecosystems, on several different time scales, affecting the abundance, distribution and feeding relationships among components of many marine communities[1,2,3,4,5,6]. While we are still working towards a complete understanding of the causes of the observed phenomena, recent projections indicate that a number of climate change scenarios have the potential to affect marine ecosystems in even more fundamental ways. These changes are related both to long-term trends in the ocean environment and to the cyclic variation in ocean conditions observed in many areas. These changes are important in their own right, but even more so because of the dependence of many of our coastal communities on living marine resources – for food, recreation, and cultural fulfillment. Over half of the U.S. population now lives within 100 miles of the coast, and this proportion is increasing dramatically. Our $60 billion per year seafood industry, marine tourism industries, recreational activities, and the very existence of some communities may be dependent on changing ocean conditions affecting marine ecosystems.

Changing climate is one of the most significant long-term influences on the structure and function of marine ecosystems and must therefore be accounted for in NOAA's management and stewardship goals to ensure healthy and productive ocean environments. Changes and variations in climate may directly or indirectly impact marine ecosystems. This includes changes and variations of sea surface temperature, ocean heat content, sea level, sea ice extent, freshwater inflow and salinity, oceanic circulation and currents, pH, and carbon inventories. Each of these properties of the global ocean is being measured to varying degrees by NOAA. Through the continued collection of data and the implementation and integration of observing systems, we strive to create longer, more globally inclusive data records that will improve our understanding

---

[1] Scavia, Donald, John C. Field, Donald F. Boesch, Robert W. Buddemeier, Virginia Burkett, Daniel R. Cayan, Michael Fogarty, Mark A. Harwell, Robert W. Howarth, Curt Mason, Denise J. Reed, Thomas C. Royer, Asbury H. Sallenger, and James G. Titus. 2002. Climate Change Impacts on U.S. Coastal and Marine Ecosystems. Estuaries Vol. 25, No. 2, p. 149–164

[2] Grebmeier, J. M., J. E. Overland, S. E. Moore, E. V. Farley, E. C. Carmack, L. W. Cooper, K. E. Frey, J. H. Helle, F. A. McLaughlin, and S. L. McNutt, 2006, A major ecosystem shift in the northern Bering Sea, Science, 311: 1461-1464.

[3] Drinkwater, K. F., A. Belgrano, A. Borja, A. Conversi, M. Edwards, C. H. Greene, G. Ottersen, A. J. Pershing, and H. Walker, 2003, The response of marine ecosystems to climate variability associated with the North Atlantic Oscillation, In: The North Atlantic Oscillation: Climate Significance and Environmental Impact, Am. Geophys. Union, Geophys. Mono. 134: 211-234.

[4] Hoegh-Guldberg, O., 1999, Climate change, coral bleaching and the future of the world's coral reefs. Marine and Freshwater Research 50: 839-866.

[5] Loeb, V., V. Siegel, O. Holm-Hansen, R. Hewitt, W. Fraser, W. Trivelpiece, and S. Trivelpiece, 1997, Effects of sea-ice extent and krill or salp dominance on the Antarctic food web, Nature, 387: 897-900.

[6] Mantua, N. J., S. R. Hare, Y. Zhang, J. M. Wallace, and R. C. Francis, 1997, A Pacific interdecadal climate oscillation with impacts on salmon production, Bull. Am. Meteorol. Soc., 78: 1069-1079.

of climate change and our ability to reliably predict impacts on marine ecosystems over time scales of interest to our constituents now (e.g., 5-10 year time horizon) and in the future.

**A Paleontological Perspective on the Impacts of Climate Change on Marine Ecosystems**

The paleoclimate record provides a long view of how populations and entire ecosystems have responded to climate change over hundreds to thousands of years. Many sources of paleoclimate data are from biological indicators such as tree rings, corals, and fossil plankton. By comparing the time series from biological indicators with paleoclimate data from non-biological material such as ice cores, boreholes, and cave stalagmites, one can reconstruct not only how climate has changed, but also how marine and terrestrial populations have responded.

Over hundreds of thousands of years, ice ages have come and gone, and populations have responded by changing growth patterns, abundance and geographic location. Remarkably only a few documented extinctions occurred in terrestrial and marine ecosystems during ice age cycles, apart from the extinction of the Pleistocene megafauna (e.g., the woolly mammoth). Just as the changes in climate during the ice ages were large and sometimes abrupt, ecosystem changes were similarly large and abrupt. For example, at the end of the last ice age, pollen from lake sediments indicate an abrupt northward migration and establishment of the modern biomes across North America[7], while in the adjacent oceans fossil plankton from marine sediments reveal that the region where certain plankton species were abundant also moved to higher latitudes[8].

While these changes in the ocean environment were abrupt compared to the radiation changes that caused the ice ages, the changes were slow compared to the changes occurring in the current millennium. The end-of-the-ice-age ecosystem changes occurred over thousands of years. Over the last 10,000 years climate has remained relatively stable apart from small changes caused by the changes in seasonal solar radiation. Over the past 1,000 years, where the paleoclimate record is most complete, climate has been even more constant except for the recent trends in temperature and rainfall. The climate of the last 1,000 years can be characterized as: 1200-1400 AD - slightly warmer than average conditions; 1500-1800 AD - slightly cooler than average conditions; and 1900-2000 AD - an increase in the last centuries to temperatures that are likely to be the warmest in the last millennium[9,10]. Companion biological records show that organisms and ecosystems are changing in growth pattern, abundance, and other characteristics in ways that are unusual compared to the preceding 1,000 years. Detailed information on terrestrial and

---

[7] COHMAP Project Members, 1988, Climate changes of the last 18,000 years: Observations and model simulations, Science, 241: 1043-1052.

[8] CLIMAP Project Members, 1981, Seasonal reconstruction of the Earth's surface at the last glacial maximum, Geol. Soc. Am., Map and Chart Series, MC-36: 1-18.

[9] Jones, P. D. and M. E. Mann, 2004, Climate Over Past Millennia, Reviews of Geophysics, 42(2), RG2002, doi:10.1029/2003RG000143.

[10] Moberg, A., D. M. Sonechkin, K. Holmgren, N. M. Datsenko, and W. Karlén, 2005, Highly variable Northern Hemisphere Temperatures Reconstructed from Low- and High-Resolution Proxy Data, Nature, 433: 613 - 617.

marine ecosystem responses to past climate change is detailed on the NOAA Paleoclimatology web site (www.ncdc.noaa.gov/paleo). One selected example relevant to marine ecosystems involves the long record of sockeye salmon populations in Alaska.

The paleoclimate record of sockeye salmon from Alaskan lakes reveals the difficult task of separating the influence of natural climate cycles, recent climate change, and fishing pressure on salmon abundance. Sockeye salmon return to lakes in Alaska to spawn, and their remains are reflected in chemical (e.g., nitrogen-15) concentrations in lake sediments, creating a 2000 year-long record of salmon abundance. Dr. Bruce Finney, from the University of Alaska, and his colleagues correlated centuries-long cycles in salmon abundance with climate variations from other paleo proxies, demonstrating the existence of natural cycles in salmon populations prior to significant human activity in the region[11]. Near the end of the record the decline due to intense fishing pressure in the last century is also evident. Finney and colleagues note that natural cycles in salmon abundance appear out of phase with the abundance of other fish species farther south in the California Current system, a pattern they also attribute to natural climate variability. In addition to fish abundance, paleo-ecological records have also been developed for plankton that form the base of the food chain. Compared to the fish proxies, the plankton records are more complete and subject to fewer uncertainties. While these records are continuously being developed, the records published so far document a clear link between climate change and marine ecosystems. One important conclusion from this work is that marine ecosystems are sensitive to even small changes in climate.

## Current and Projected Impacts of Climate Change on Marine Ecosystems and Living Marine Resources

### *Impacts of Sea Level Rise on Ecosystems*

Sea level rise is projected to accelerate during the 21st century, with the most significant impacts in low-lying regions where subsidence and erosion problems already exist. Rising sea level has worldwide consequences because of its potential to alter ecosystems and habitat in coastal regions. Sea level rise and global climate change issues in the coastal zone include:

- Higher (deeper) and more frequent flooding of wetlands and adjacent shores;
- Increased flooding due to more intense storm surge from severe coastal storms;
- Increased wave energy in the nearshore area;
- Upward and land-ward migration of beaches;
- Accelerated coastal retreat and erosion;
- Saltwater intrusion into coastal freshwater aquifers;
- Damage to coastal infrastructure; and

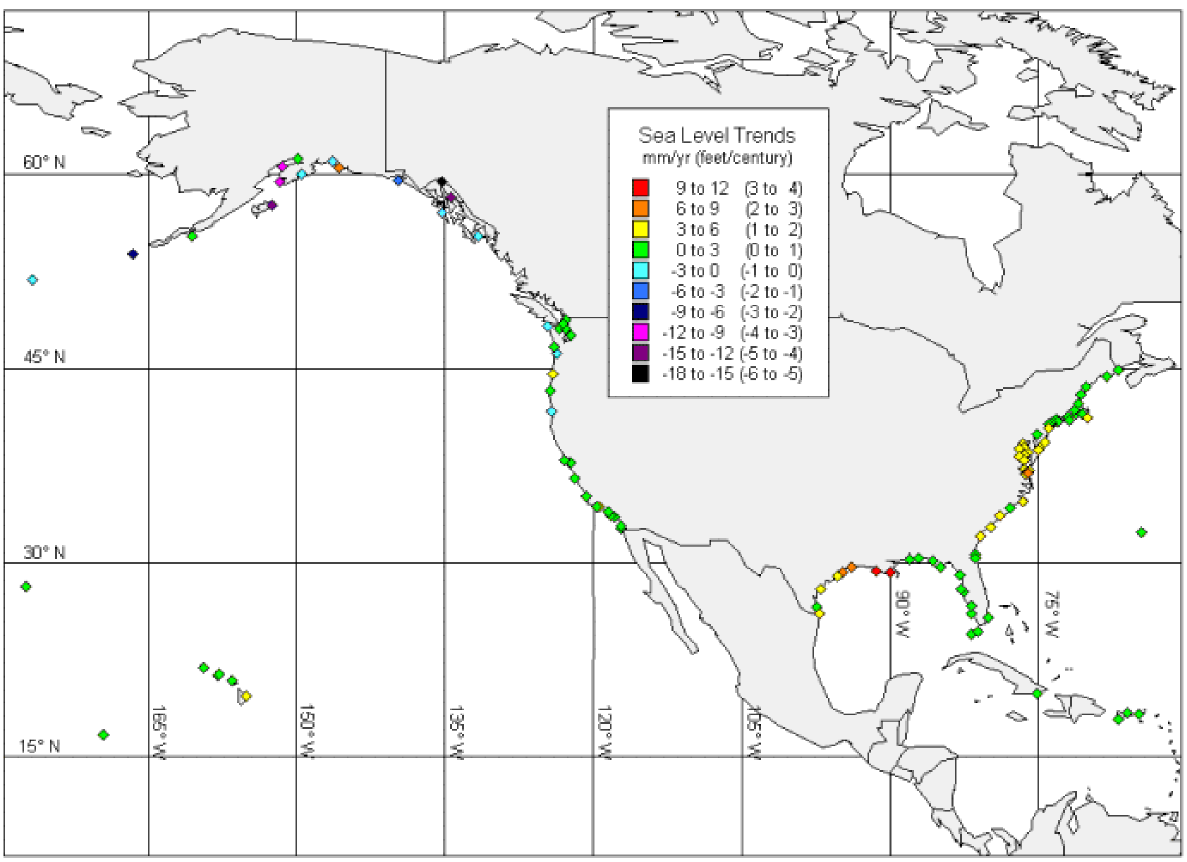
[11] Finney, B. P., I. Gregory-Eaves, M. S. V. Douglas, and J. P. Smol, 2002, Fisheries productivity in the northeastern Pacific Ocean over the past 2,200 years, Nature, 416: 729-733.

- Broad impacts on the coastal economy.

The coastlines of our Atlantic and Gulf states, as well as portions of the Alaska coastline are especially vulnerable to long-term sea level rise. The slope of these areas is so gentle that any small rise in sea level can produce a large inland shift of shoreline.

Sea level rise threatens to alter wetland ecosystems. Sea level rise may also result in increased susceptibility to nutrient-related eutrophication, due to changes in estuarine circulation. Changes in the wetland and estuarine processes will affect resident marine organisms and the fisheries dependent upon them.

NOAA has maintained long-term continuously operating stations of the National Water Level Observation Network (NWLON), and has recently documented the relative sea level trends at all of the longest term stations (1854 – present). The map below (also available at http://tidesandcurrents.noaa.gov/sltrends/slrmap.html) shows sea level trends for the United States for those locations where tide stations exist. This map provides an indication of the differing rates of relative sea level rise (vertical land and sea level motion combined) around the United States. There is a general scientific agreement that sea level rise is occurring at a global average rate of 2 mm per year. Referring to the map the mid Atlantic and Gulf Coast are experiencing 3-5 mm and 5-15 mm per year rise in sea level, respectively.



One area particularly vulnerable to sea level rise is coastal Louisiana. The graphic above illustrates that these areas are projected to have sea levels rise 3-4 feet over the next century. Factors contributing to sea level rise in coastal Louisiana are complex and multifaceted, including land subsidence due to petroleum extraction, declining sediment loads deposited from rivers into the marshes, land use practices exacerbating wetlands loss, and rising sea levels due to global climate change and other factors. Whatever the causes, a 3-4 foot rise in sea level in coastal Louisiana will have profound effects on marine resources, since coastal marshes there are important nursery areas for most of the valuable living resources (e.g., shrimp, oysters, many finfish species) in the Gulf of Mexico. In addition, loss of Louisiana's coastal marshes to sea level rise makes coastal communities much more vulnerable to recurring storm events.

The Northwestern Hawaiian Islands (NWHI) are of particular concern with respect to sea level rise. The NWHI have high conservation value due to their concentration of endemic, endangered and threatened species, and large numbers of nesting seabirds. Most of these islands are low-lying and therefore potentially vulnerable to increases in global average sea level. The potential for NWHI habitat loss was recently assessed by the NMFS Pacific Islands Fisheries Science Center, by creating topographic models of several islands and atolls in the NWHI and evaluating the potential effects of sea-level rise by 2100 under a range of basic passive flooding scenarios. Projected terrestrial habitat loss varied greatly among islands: 3% to 65% under a median scenario (48-cm rise), and 5% to 75% under the maximum scenario (88-cm rise). Spring tides may repeatedly inundate all land below 89 cm (median scenario) and 129 cm (maximum scenario) in elevation. Sea level is expected to continue increasing after 2100, which would have greater impact on atolls such as French Frigate Shoals and Pearl and Hermes Reef, where virtually all land is less than 2 m above sea level. Higher islands such as Lisianski, Laysan, Necker, and Nihoa may provide longer-term refuges for species. The effects of habitat loss on NWHI biota are difficult to predict, but may be greatest for endangered Hawaiian monk seals, threatened Hawaiian green sea turtles, and the endangered Laysan finch at Pearl and Hermes Reef.

### *Ocean Acidification*

The oceans are the largest natural long-term reservoir for carbon dioxide, absorbing approximately one-third of the carbon dioxide added to the atmosphere by human activities each year. Over the past 200 years the oceans have absorbed 525 billion tons of carbon dioxide from the atmosphere, or nearly half of the fossil fuel carbon emissions over this period. Over the next millennium, the global oceans are expected to absorb approximately 90% of the carbon dioxide emitted to the atmosphere[12].

For over 20 years, NOAA has participated in decadal 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 confirm that oceans are absorbing increasing amounts of carbon

[12] Archer, D. E., H. Kheshgi, E. Maier-Reimer, 1998, Dynamics of fossil fuel $CO_2$ neutralization by marine $CaCO_3$, Global Biogeochemical Cycles, 12: 259-276.

dioxide. Estimates of future atmospheric and oceanic carbon dioxide concentrations, based on the Intergovernmental Panel on Climate Change 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. To put this in historical perspective, this surface ocean pH decrease would be lower than it has been for more than 20 million years[13].

Recent studies indicate that such changes in water chemistry, or ocean acidification as the phenomenon is called, would have effects on marine life, such as corals and plankton[13,14]. The carbonate chemistry of seawater has a direct impact on the dissolution rates of calcifying organisms (coral reefs and marine plankton). As the pH of the oceans decreases and becomes more acidic, some species of marine algae and plankton will have a reduced ability to produce protective calcium carbonate shells. This makes it more difficult for organisms that utilize calcium carbonate in their skeletons or shells to build and maintain their structures. These organisms form the foundation of the food chain, upon which other marine organisms feed. Decreased calcification may also compromise the fitness or success of these organisms and could shift the competitive advantage towards organisms not dependent on calcium carbonate. Carbonate skeletal structures are likely to be weaker and more susceptible to dissolution and erosion. There is paleooceangraphic evidence that during the last high $CO_2$ regime (55 million years ago) increased ocean acidification was associated with mass extinctions of phytoplankton species, followed by a recovery period of about 80,000 years[15]. Because of the importance of phytoplankton to marine food webs, biodiversity and productivity of the oceans may be altered[14], which may result in adverse impacts on fishing, tourism, and other economies that rely on the continued health of our oceans.

Recent findings indicate that such conditions could develop within decades at high latitudes[14]. This will likely have impacts on high latitude ecosystems because pteropods, a shelled, swimming mollusk, is a significant prey item for fish in these regions. It is important to gain a better understanding of how ocean chemistry and biology will respond to higher carbon dioxide conditions so that predictive models of the processes and their impacts on marine ecosystems can be developed.

---

[13] Feely, R. A., C. L. Sabine, K. Lee, W. Berrelson, J. Kleypas, V. J. Fabry, and F. J. Millero, 2004, Impact of anthropogenic $CO_2$ on the $CaCO_3$ system in the oceans, Science, 305(5682): 362-366.

[14] Orr, J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Fruber, 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. Totterdel, M.-F. Weirig, Y. Yamanaka, and A. Yool, 2005, Anthropogenic ocean acidification over the twenty-first century and its impact on calcifying organisms, Nature, 437: 681-686.

[15] Zachos, J. C., U. Röhl, S. A. Schellenberg, A. Sluijs, D. A. Hodell, D. C. Keely, E. Thomas, M. Nicolo, I. Raffi, L. J. Lourens, H. McCarren, and D. Kroon, 2005, Rapid acidification of the ocean during the Paleocene-Eocene thermal maximum, Science, 308: 1611-1615.

***Coral Bleaching Events***

Coral reef ecosystems are among the most diverse and biologically complex ecosystems on Earth and provide resources and services worth billions of dollars each year to the United States economy and economies worldwide. Coral reefs support more species per unit area than any other marine environment, including about 4,000 species of fish, 800 species of hard coral and thousands of other species. Approximately half of all federally-managed fish species depend on coral reefs and related habitats for a portion of their life cycles. The National Marine Fisheries Service estimates the annual commercial value of U.S. fisheries from coral reefs is over $100 million. Local economies also receive billions of dollars from visitors to reefs through diving tours, recreational fishing trips, hotels, restaurants, and other businesses based near reef ecosystems. In the Florida Keys, for example, coral reefs attract more than $1.2 billion annually from tourism. In addition, coral reef structures buffer shorelines against waves, storms and floods, helping to prevent loss of life, property damage and erosion.

Coral reefs are extremely vulnerable to increased sea surface temperatures. As global temperatures have risen over the past 30 years, there has been a corresponding increase in the extent and frequency of extremely high sea surface temperatures and coral bleaching events in many tropical regions[4,16].

Coral bleaching is a response of corals to unusual levels of stress primarily thought to be associated with light and ocean temperature extremes. Bleaching occurs when corals expel their symbiotic algae and lose their algal pigment. Loss of the symbiotic algae leaves the coral tissue pale to clear and, in extreme cases, causes a bleached appearance. Corals often recover from mild bleaching. However, if the stress is prolonged and/or intense, the corals may die or weaken, causing them to be more susceptible to disease and other stressors.

Coral bleaching has occurred in both small localized events and at large scales. Although many stressors can cause bleaching, mass bleaching events have almost exclusively been linked to unusually high ocean temperatures. There is still much that we do not know about the impacts of bleaching-associated mass coral mortality on: (1) the function of coral reef ecosystems; (2) the associated fisheries; and (3) the value (loss) to recreation and tourism industries.

Through satellite and *in situ* monitoring of thermal stress, NOAA tracks the conditions that may lead to coral bleaching. When the data show that conditions are conducive to bleaching, NOAA provides watches, warnings, and alerts to users throughout the globe through NOAA's Coral Reef Watch project and Integrated Coral Observing Network. Coral bleaching alerts allow managers and scientists to deploy monitoring efforts which can document the severity and impacts of the bleaching to improve our understanding of the causes and consequences of coral bleaching.

Large scale or mass bleaching events were first documented in the eastern Pacific in the early 1980's in association with the El Niño Southern Oscillation[16]. In 1997-98, coral bleaching

[16] Brown, B. E., 1997, Coral bleaching: causes and consequences, Coral Reefs 16(5): S129-S138.

became a global problem when a strong El Niño (period of warmer than average water temperature), followed by a La Niña (period of colder than average water temperature) caused unprecedented coral bleaching and mortality world-wide[17].

However, coral bleaching events are not only tied to the El Niño/La Niña phenomena. In 2005, a year lacking El Niño or La Niña climate patterns, unusually warm temperatures were recorded in the tropical North Atlantic, Caribbean, and Gulf of Mexico. Corals in the Caribbean region experienced temperatures in 2005 that greatly exceeded any of the previous 20 years. While the thermal stress in the Caribbean has increased over the last 20 years, 2005 was a major anomaly from the upward trend in temperatures there. As a result of NOAA satellite and *in situ* monitoring, we were able to alert managers and scientists to this temperature anomaly. The unusually warm temperatures gave rise to the most intense coral bleaching event ever observed in the Caribbean. NOAA is working with local partners in Florida, Puerto Rico and the U.S. Virgin Islands to better assess the impacts from the 2005 bleaching event. It is clear that mass bleaching is a serious concern to the communities that depend upon these resources.

Preliminary analyses by NOAA show that the cumulative thermal stress for 2005 was 50% larger than the cumulative stress of the prior 20 years combined[18]. September 2005 was by far the warmest September in the Eastern Caribbean in the entire 100-year record. Many areas, including the U.S. Virgin Islands, averaged over 90% of their corals bleached and some have already lost 30% of these corals due to direct thermal stress or subsequent disease. NOAA is currently analyzing the impact of this bleaching event on already vulnerable elkhorn and staghorn coral species. These two species have been proposed for listing as "threatened" under the Endangered Species Act.

NOAA and the Department of the Interior (DOI) are leading the interagency effort of the U.S. Coral Reef Task Force to respond to and assess the massive coral bleaching event in the Caribbean region in 2005. This effort has engaged many government and non-government partners from across the region to assess the impacts of the massive event and make recommendations on how to prepare for and address future events. For example, NOAA, DOI, and the National Aeronautics and Space Administration (NASA) conducted missions in October and December 2005 to examine the extent of bleaching and recovery/mortality of corals within the Buck Island Reef National Monument, as well as obtain aerial and hyperspectral imagery to quantify the extent of bleaching within St. Croix, St. John, and southwestern Puerto Rico. Initial findings indicate that in many areas, including the U.S. Virgin Islands, over 90% of coral cover had bleached. While some recovery had occurred by December, hardest hit areas have already had over 30% of their coral die. Further analyses are currently underway.

---

[17] Wilkinson, C. R., 2000, Status of Coral Reefs of the World: 2000. Townsville, Australia, Australian Institute of Marine Science.

[18] Eakin, C. M. et al., 2006, Record-Setting Coral Bleaching the Result of Thermal Stress, intended for Science, in preparation.

***Impacts of Climate on Fisheries and Protected Resources***

NOAA has stewardship responsibilities for coastal and living marine resources from over 90 acts of Congress. Resources managed under these authorities are extremely valuable to the country, with fisheries alone contributing over $60 billion a year and 520,000 jobs to the U.S. economy. Interannual climate variability (e.g., El Niño, La Niña) and trends (e.g. global warming) can cause profound geographic shifts in marine ecosystems and are of great consequence to fishery-dependent communities. Climate variability/change impacts environmental conditions on multiple time scales, ranging from interannual to decadal; since earth's temperature is warming on a global scale, it is important to assess the environmental impacts on large marine ecosystems.

In the past several decades, there have been significant changes in the distribution, growth, and abundance of living marine resources resulting from changes in ocean temperatures and related ocean conditions. These changes have occurred in polar regions, in temperate waters, and in the tropics. These changes have altered the productivity and structure of marine food webs and change the flow of goods and services to coastal communities. Below are cited some specific examples of ecosystems changes documented by NOAA that are likely linked to climate variations.

**Polar Regions:** Loss of sea ice at high latitudes has been documented in a number of recent scientific articles and other forums. Until recently, the northern Bering Sea ecosystem had extensive seasonal sea ice cover and high water column and sediment carbon production. Recently, NOAA researchers and other colleagues have demonstrated that these ecosystems are shifting away from these characteristics [2,19]. The amount and duration of ice coverage in the southeast Bering Sea has decreased substantially since the early 1970s. In addition, the southeast Bering Sea has warmed 2-3ºC over the past 10 years. Recent work has documented differences in ice coverage and thickness as far north as St. Lawrence Island in the northern Bering Sea. These changes have substantial impacts to both arctic and subarctic marine species in the area. For example, Greenland turbot, a flatfish that prefers cold temperatures, has shown a steady decrease in abundance since the mid-1970s. During this same time period, abundance of walleye pollock, which prefers warmer waters, has increased dramatically, with the present landings valued at $295 million per year. Bering Sea snow crab distribution has shifted northward, and pollock distribution in the Bering Sea may soon follow, affecting ecosystem interactions, fishery assessment surveys and the economics of the fishing fleet which have to travel farther and spend more days at sea to find and capture the same number of fish. In addition, juvenile pollock act as forage fish in this ecosystem and changes in their abundance, size, or distribution has the potential to affect marine mammals.

Changes in the Bering Sea marine mammals have also been observed. Gray whales have shifted their distributions northward, apparently in response to decreases in sea ice and declines in their

---

[19] Overland, J. E., and P. J. Stabeno, 2004, Is the climate of the Bering Sea warming and affecting the ecosystem? EOS Trans. Am. Geophys. Union, 85(33): 309-316.

preferred prey on the ocean floor[20]. In addition, ice-dependent seals (ring, spotted, bearded, and ribbon seals) require ice for parts of their life history (molting and pupping) and there is concern that these animals are being forced away from suitable feeding grounds as the ice retreats[21]. Similar concerns have been expressed regarding polar bear and walrus populations in Alaska[21,22]. These changes to the ecosystem have clear implications for subsistence harvests in Alaskan native communities.

In addition to the effects of climate variability and change on the distribution and abundance of commercially important species of fish and shellfish, as well as marine mammal species important to subsistence hunters, the reduction in the extent and duration of sea ice in the Bering and Chukchi Seas in recent years has led to serious erosion problems for several remote villages and towns, including Barrow, Pt. Lay, Wales, and particularly in the village of Shishmaref. In these villages, traditionally the sea ice would buffer the impacts of storm driven waves during the winter and spring. With less sea ice, wave action is causing serious erosion problems and threatening buildings and roads. To better predict the likely rate at which erosion will impact this area, requires better information on trends in sea level height, extent and duration of sea ice, and storm frequency.

Decreases in sea ice appear to be affecting other ecosystems as well. The annual air temperature near the South Shetland Islands, Antarctica has warmed by over 4ºC since the 1940's[23] and ice extent around areas of Antarctica monitored by NOAA has declined appreciably[24]. Air temperatures at Palmer station are closely correlated with the annual amount of ice cover. While air temperatures in the Shetlands have increased, the density of krill, a shrimp-like organism that is the central link in the Antarctic food web has decreased by more than 90% in the region since 1976[25]. Warming of Antarctic waters and loss of ice affect predator (seals, penguins, whales, etc.) and krill populations in the Southern Ocean in several ways. Krill are a keystone species in the Antarctic because so many species (fish, seals, penguins, sea birds, whales) feed upon them. Declines in krill populations will negatively affect populations of krill predators. Over the past two decades, populations of Adelie and chinstrap penguins have declined significantly on the Antarctic Peninsula, and the average reproduction rate of fur seals in the South Shetlands has slowed as well. Years of low sea ice appear to be associated with low krill production but relatively high populations of salps (a gelatinous zooplankton, of little nutritional value to krill predators)[5]. In addition, some predators are dependent upon sea ice to haul out and rest during

[20] Moore, S. E., J. M. Grebmeier, and J. R. Davies, 2003, Gray whale distribution relative to forage habitat in the northern Bering Sea: current conditions and retrospective summary, Can. J. Zool., 81: 734-742.

[21] Tynan, C.T., and D.P. DeMaster, 1997, Observations and predictions of arctic climate changed: potential effects on marine mammals, Arctic, 50: 308-322.

[22] Stirling, I., Lunn, N.J., and Iacozza, J. 1999. Long-term trends in the population ecology of polar bears in western Hudson Bay in relation to climatic change. Artic 52: 294-306.

[23] Smith, R. C. and S. E. Stammerjohn, 2001, Variations of surface air temperature and sea-ice extent in the western Antarctic Peninsula region, Ann. Glaciol., 33: 493-500.

[24] Hewitt, R. P. and E. H. Linen Lowe, 2000, The Fishery on Antarctic Krill: Defining an ecosystem approach to management, Rev. Fish. Sci., 8(3): 235–298.

[25] Atkinson, A., V. Siegel, E. Pakhomov, and P. Rothery, 2004, Long-term decline in krill stock and increase in salps within the Southern Ocean, Nature, 432: 100-103.

the over-wintering migrations, and declines and shifts in sea-ice will impact their movements and distributions. Thus, climate-related changes in the environment of Antarctica have had and will likely continue to have important consequences for the marine ecosystems of the region.

**Temperate Regions**: Climate-induced shifts in species distribution and abundance have been observed in the temperate regions of the Atlantic and Pacific. Many marine fish species have been observed to shift their distributions northward in response to warming waters[3,26]. Populations of surf clams, an economically important species along the mid-Atlantic coast of the United States (particularly from New Jersey to Virginia), show evidence of increased mortality in the southern regions of their territory. This is thought to be due to elevated sea temperatures[27]. These populations are also susceptible to low oxygen events that may increase in frequency and severity with the anticipated warming in the Mid-Atlantic region. A severe low oxygen event off New Jersey in 1976 caused economic losses of over $70 million to the clam fishery and it was many years before the clam populations recovered[28]. Declining recruitment levels of some species linked to cooler water temperature (e.g., yellowtail flounder in Southern New England) impedes rebuilding of the stock to provide long-term sustainable fisheries.

In the western North Atlantic, a study of the distribution patterns of three dozen pelagic and demersal fish species was conducted using consistent data from over three decades to examine impacts of water temperature changes on geographic distributions[25]. This study revealed a set of species whose center of distribution shifts from 0.5-0.9 degrees of latitude pole-ward for each degree Celsius of water temperature increase. Because not all species responded in this manner, there is likelihood that the structure of predator-prey relationships in the ecosystem would be altered under a scenario of long term warming of Atlantic waters[17,24]. Studies from the eastern Atlantic have drawn similar conclusions. In the southern North Sea, there has been a gradual replacement of species with primarily cold water affinities with ones previously associated with more southern waters[29].

In the California Current ecosystem there have also been sustained shifts in the dominance of various fish species over the past few decades. Off California, the dominant fish fauna has shifted from cold-water species to ones of primarily warm water affinities. These changes have occurred gradually over a sustained two decade period, and are confounded by overfishing of many of the stocks.

From the 1970s through the 1990s there were overall declines in the California fishery landings that coincided with an unprecedented period of unusually warm ocean conditions and a decline

---

[26] Murawski, S. A., 1993, Climate change and marine fish distributions: Forecasting from historical analogy, Trans. Am. Fish. Soc., 122: 647-658.

[27] Weinberg, J.R., T.G. Dahlgren, and K.M. Halanych. 2002. Influence of rising sea temperature on commercial bivalve species of the U.S. Atlantic coast. In N. McGinn, editor. Fisheries in a changing climate. American Fisheries Society, Symposium 32, Bethesda, MD.

[28] Swanson, R. L. and C. J. Sinderman, 1979, Oxygen depletion and associated benthic mortalities in New York Bight, 1976, NOAA Professional Paper 11.

[29] Perry, A. L., P. J. Low, J. R. Ellis, and J. D. Reynolds, 2005, Climate change and distribution shifts in marine fishes, Science, 308: 1912-1915.

in ecosystem productivity[30]. Changes in the survival of Pacific salmon appear to follow a decadal-scale cycle (the Pacific Decadal Oscillation, or PDO), with salmon survivorship being relatively high during the cool periods and low during warm periods[6]. In addition the California sardine collapse in the 1940s was driven in part by a shift to cooler conditions and a different ecosystem structure. Ocean sediment records indicate sardine biomass has fluctuated for centuries on time scales associated with decadal-scale shifts in the north Pacific temperature[31].

Climate and weather patterns over the North Atlantic are strongly influenced by the relative strengths of two large-scale atmospheric pressure cells – the Icelandic Low and a high pressure system generally centered over the Azores in the eastern Atlantic. A deepening of the Icelandic Low often corresponds with a strengthening of the Azores High and vice versa. This see-saw pattern is called the North Atlantic Oscillation (NAO) and a simple index of its state is given by the difference in sea level pressure between the Azores and Iceland.

When the NAO index is positive, we see an increase in westerly winds across the Atlantic and in precipitation over southeastern Canada, the eastern seaboard of the United States, and northwestern Europe[3]. We also see increased storm activity tracking towards Europe. Water temperatures are markedly low off Labrador and northern Newfoundland, and warm off the United States. Conversely, when the NAO index is negative, we have decreased storminess, and drier conditions over southeastern Canada, and colder conditions over the eastern United States and northwestern Europe. Water temperatures are warmer off Labrador and Newfoundland, but cooler off the eastern United States. These changes in the state of the North Atlantic Oscillation show a tendency to persist on decadal timescales. The NAO was generally positive during the 1980's and 1990's but has shown a tendency to decrease since about the year 2000.

Variation in the NAO has very different effects on cod recruitment on the western and eastern Atlantic[3]. The direction of the NAO effect on cod recruitment exhibits patterns consistent with the regional manifestation of the NAO in the North Atlantic, with a coherence in the NAO effect in northern Canada and Iceland and between southern Canada-United States and western Europe. The decline in cod in areas such as the North Sea has been linked to the interplay of over-exploitation and changes in the planktonic ecosystem affecting the food supply of larval cod (which is in turn affected by the NAO). Specifically, the supply of the copepod *Calanus finmarchicus* declined during positive NAO conditions and was replaced by smaller bodied species, apparently less suitable as food for larval cod.

In the Northwest Atlantic, researchers have suggested a linkage between oceanographic conditions related to the North Atlantic Oscillation, abundance of the copepod *Calanus finmarchicus*, and the calving success of the endangered right whale in Gulf of Maine[32].

---

[30] Roemmich, D. and J. McGowan, 1995, Climatic warming and the decline of zooplankton in the California Current, Science, 267: 1324-1326.
[31] Baumgartner, T. R., A. Soutar, V. Ferreira-Bartrina, 1992, Reconstruction of the history of Pacific sardine and northern anchovy populations over the past two millennia from sediments of the Santa Barbara Basin, California, CalCOFI Rep. 33: 24-40.
[32] Greene, C. H., A. J. Pershing, R. D. Kenney, and J. W. Jossi, 2003, Impact of climate variability on recovery of endangered North Atlantic right whales, Oceanography, 16: 96-101.

Abundance of adult *Calanus* declined with these water mass changes and a concomitant decline in the birth rate of right whales was observed. The decline in the calving success comes at a time when other human impacts such as ship strikes threaten recovery of this species. These observations suggest that climate-induced changes can have far reaching ramifications for commercially important fish species throughout the North Atlantic and for critically endangered marine mammal species.

These examples of climate related effects on marine ecosystems are just a sample from the growing body of evidence linking climate change to marine ecosystem function. All of these changes, whether trended or variable over some time scale, may have profound implications for the health and viability of marine ecosystems and for the human communities that are dependent upon them. It is our challenge to understand these linkages both to better predict their effects and to identify the conservation and management policies in the face of climate variability and change that may help to mitigate their effects.

Various management authorities have responded. For example, the Pacific Fisheries Management Council routinely takes into account decadal-scale changes in marine productivity regimes when setting harvest policies for Pacific groundfish and other species. Similar management responses are being used or contemplated in other living marine resource arenas in which NOAA participates.

## Ongoing Challenges for Improving Climate and Ecosystems Information

Marine ecosystems and their component parts have proved to be sentinels of climate change and ocean variability. Changes in living marine resources, when observed at proper scales, give us new information about how changes in climate are affecting the earth, and have opened new avenues of research into understanding the importance of human activities contributing to these observed changes. It is vital that we improve our understanding of past, current and projected ecosystem impacts of climate change in order to improve the stewardship of these resources. Management policies we use in living marine resource management can either help mitigate or exacerbate changes due to impacts of climate variation. Below I detail a few of NOAA's scientific priorities in improving the predictability of ecosystem responses to climate change.

### *Regional Climatologies*

Regional impacts of climate variability and change are important and are being studied. In fact, some region-specific modeling predicts that part of the planet – and the marine environment – will experience cooler and/or wetter conditions, while other areas will be hotter and drier. Therefore, regional ecosystem responses may result in stable or increasing resources in one region while at the same time resulting in declines in abundance and distribution shifts elsewhere.

Understanding these regional impacts on marine and associated terrestrial ecosystems will require more detailed regional models and data linking global climate variations to regional atmospheric and ocean conditions. This requirement is consistent with NOAA's focus over the last five years to integrate multidisciplinary research at the Large Marine Ecosystem level. Eight such marine ecosystems have been recognized in the U.S. Exclusive Economic Zone. It is at the ecosystem scale where we expect to be able to fully realize how anthropogenic effects (e.g., fishing, land use practices, pollution) and naturally driven environmental variation combine to produce the current abundance levels and composition of species in each of our marine ecosystems.

The following will help improve our understanding the ecosystem consequences of climate change:

### *Improved Climate and Ecosystem Modeling*

Extreme weather events as well as long term trends in atmospheric and ocean conditions necessitate that we further improve our predictive understanding of the climate system and its impacts on ecosystems. To do so, NOAA believes that expanded earth and ecosystems modeling could serve as a tool for studies of: (1) the impacts of climate variability and change on land ecosystems, ocean ecosystems and carbon cycling; (2) the strength of ecological and carbon feedbacks on climate (e.g. the effects of increasing atmospheric carbon dioxide on plant growth, which in turn affects distributions of atmospheric carbon dioxide); and (3) improved predictions of the impacts of climate trends on regional large marine ecosystems and their species. An expanded earth and ecosystems model capability would take advantage of the current suite of weather, air quality, climate variability, and ecosystem models to include biogeochemical cycling, dynamic vegetation, atmospheric chemistry, and anthropogenic forcing (e.g. carbon and aerosols) of climate. Existing hydrodynamic models of ocean circulation would be expanded to include trophic interactions, primary productivity, and spatial distributions and movement models for specific taxa, among other ecological phenomena. It would employ a unified modeling framework, enabling integration of a comprehensive suite of physics, assimilation, biogeochemical, and ecosystem model components.

As model development progresses, components will be expanded to include: (a) a land model (currently under evaluation) that simulates dynamic land vegetation and land use changes, as well as the exchange of water and energy between land, vegetation, and atmosphere; (b) a comprehensive ocean biogeochemical model (under refinement) and (c) state-of-the-art marine ecological models incorporating ocean circulation and spatially explicit processes.

Comprehensive earth-ecosystems models have a wide range of applicability for managers of marine ecosystems, including:

- Short term (6 months to 1 year) and medium term (2-5 year) projections of the regional response of fisheries and protected species to climate change
- Seasonal-interannual prediction of the abundance and distribution of marine populations;
- Seasonal forecasting of coral bleaching potential and assessment of the long-term impact of climate variability and change on coral bleaching frequency;

- Assessments of the health of coastal ecosystems under the stress of pollution and runoff;
- Predictions of harmful algal blooms and eutrophication zones;
- Identification of impact of climate change on species diversity;
- Analysis relating to land use practices and climate;
- Design of marine protected areas and other management measures;
- Predictions of pollution transport and effects on human health; and
- Understanding seasonal patterns of plant reproduction and animal migration.

In order to develop these integrated regional and global models of ecosystem response, we face a number of technical challenges. Additional research to provide the information needed to understand the underlying processes linking climate change to the response of living marine resources is critical. Many of the examples of ecological response cited above are based on statistical correlations of time series of environmental data rather than a fundamental understanding of the complex relationships responsible for the observed phenomena. Predictive models must take such complex dynamics into account. Expanded ecosystem research capabilities will be required to assess these critical links. At the same time, expanded modeling capabilities will require more comprehensive physical observations and related routine monitoring data than we have the capability to deploy today.

***Importance of the Integrated Ocean Observing System***

NOAA has a large, broad-scale and robust system of oceanographic, climate, and ecosystem measurement stations throughout the U.S. EEZ and the world. To make data from these systems available to climate and ecosystem scientists both within the U.S. and globally, NOAA is working with other federal agencies and academic and State partners to build the U.S. Integrated Ocean Observing System (IOOS). IOOS, when fully integrated, will provide more complete and improved access to observations of the oceans, including ecological and physical parameters linked to climate variability and change and requisite social and economic information, to serve multiple societal goals. IOOS will support regional climatologies and will provide information necessary to model climate impacts on ecosystems at appropriate global, regional, and local scales. Full development of IOOS is a high priority in understanding climate effects on U.S. marine ecosystems, and contributes to U.S. support of the Global Earth Observing System of Systems (GEOSS).

***Management of Living Marine Resources using Ecosystems Approaches***

Our current understanding of climate impacts on marine ecosystems points to the critical need to employ ecosystem-based approaches to monitoring, assessing, and managing living marine resources. Climate change is only one of a complex set of factors (both human induced and naturally occurring), that influence living marine resources. These include harvesting policies for fisheries, protected species recovery policies, and management of increasingly complex uses of the coastal zone for a variety of other societal needs. Effective management of resources in this complex environment means we will have to balance many competing and simultaneous objectives. NOAA is committed to advancing an ecosystem approach to its many stewardship responsibilities as a way forward in striking this balance. NOAA defines an ecosystem approach to managing living resources is one that is geographically specified, collaborative, adaptive, accounts for the broad scope of ecosystem knowledge and uncertainties, considers multiple factors affecting resources, is incremental in approach, and balances diverse societal objectives. Incorporating the effects of climate change into the conservation of living marine resources is one of the Nation's greatest and most critical challenges facing ocean ecosystems management.

Thank you Mr. Chairman, I would be pleased to answer any questions you or the other Committee members may have.