Climate Impacts on U.S. Living Marine Resources: National Marine Fisheries Service Concerns, Activities and Needs

K. E. Osgood (editor)

U.S. Department of Commerce
National Oceanic and Atmospheric Administration
National Marine Fisheries Service

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U.S. Department of Commerce
Carlos M. Gutiérrez, Secretary

National Oceanic and Atmospheric Administration
Vice Admiral Conrad C. Lautenbacher, Jr., USN (Ret.)
Under Secretary for Oceans and Atmosphere

National Marine Fisheries Service
James W. Balsiger, Acting Assistant Administrator for Fisheries

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Preface

The National Marine Fisheries Service (NMFS) is a subagency of the National Oceanic and Atmospheric Administration (NOAA) within the U.S. Department of Commerce. NMFS is responsible for the science-based management, conservation, and protection of living marine resources within the U.S. Exclusive Economic Zone and within the international arena. In regions where NMFS has living marine resource management responsibilities, it conducts assessments of living marine resources and their environment through numerous monitoring and research programs. Currently, most of these programs do not account for the climate impacts on the ecosystems.

This Climate Impacts on Living Marine Resources document was conceived to identify the regional climate related ecosystem impacts which concern NMFS. The document contains an introduction which presents an overview of the major categories of climate impacts on coastal and marine ecosystems, followed by chapters focused on the individual regional marine ecosystems for which NMFS has management responsibilities. The regional chapters highlight the major climate related ecosystem concerns of each regional ecosystem, what NMFS is currently doing to address these concerns, and what NMFS must do to adequately address these concerns. In addition, these chapters identify the climate information that will be required for NMFS to address these concerns.

This document draws upon the NOAA planning process, addressing many of the categories of climate impacts that have been identified within the NOAA program planning process. However, it is NMFS specific in that it is focused on living marine resources and the climate impacts that NMFS should be addressing in order to meet its mandates. NMFS scientists who examine environmental impacts on living marine resources at each of the regional fishery science centers contributed to, and set the priorities for, the regional ecosystem sections. These scientists frequently interact with NMFS's partners and constituents in order to identify and advance our understanding of important issues. This plan augments the NMFS Strategic Plan for Fisheries Research (NMFS, 2007) by providing detailed information on NMFS responsibilities and needs with respect to climate change.

NMFS. 2007. NMFS strategic plan for fisheries research. U.S. Dep. Commer., NOAA Tech. Memo. NMFS F/SPO-80, 170 p.

Executive Summary

With the increasing recognition that climate change is occurring and having large impacts on living marine resources, a sound ecosystem approach to management of those resources requires both understanding how climate affects ecosystems and integration of that understanding into management processes. The National Marine Fisheries Service (NMFS) must identify how changing climatic conditions will impact its mission and must be prepared to adapt to these changes. This document identifies the climate related ecosystem concerns in the regional marine ecosystems for which NMFS has living marine resource management responsibilities, what NMFS is currently doing to address these concerns, what NMFS must do going forward to address these concerns, and what climate information is needed to integrate climate into resource management. The regional ecosystems included in this analysis are: the Northeast U.S. Continental Shelf; the Southeast U.S. Continental Shelf, Gulf of Mexico, and U.S. Caribbean; the California Current Ecosystem; the Alaskan Ecosystem Complex; the Pacific Island Ecosystem Complex; the Eastern Tropical Pacific; North Pacific Highly Migratory Species; and the Antarctic.

Major Climate Induced Ecosystem Concerns

All regions for which NMFS has living marine resource management responsibilities identified some aspect of climate impacts on ecosystem productivity, phenology and species distributions as a major climate related ecosystem concern. Different aspects of this concern are deemed most critical in the separate regions, as denoted by the distinct concern names within the regional chapters. Decadal scale variability and long term changes (e.g. warming) were identified as major ecosystem concerns in all regions. Impacts identified include effects on productivity, species distributions, recruitment, community structure, and timing of biological events. These impacts indicate broad climate caused changes on marine ecosystems. For ecosystem concerns related to long-term changes including warming, all regions are likely to experience environmental conditions that have not been experienced before. In the California Current, Pacific Islands, Eastern Tropical Pacific, and for North Pacific Highly Migratory Species, the biological effects of El Niño-Southern Oscillation (ENSO) cycles were identified as an important factor. For ecosystem concerns related to climate variations such as ENSO, North Atlantic Oscillation, Pacific Decadal Oscillation, and the timing and strength of upwelling, it is important to determine how these climate variations affect the ecosystems and to know how long term climate change will impact the climate variability patterns.

The loss of sea ice is a major concern for regions of the Alaskan Ecosystem Complex and the Antarctic. The presence of sea ice is a key factor that influences the structure of these ecosystems; and sea ice extent and duration is diminishing in many areas. Sea ice provides habitat for ice dependent animals, serves as a refuge for some fish species, contains algal communities that provide food during the winter to juvenile krill in the Antarctic, and plays an important role in the timing of spring phytoplankton blooms and the balance between pelagic and benthic productivity in the Bering Sea. As sea ice retreats, species distributions are changing, reflecting the altered habitat. In addition, as ice melts, freshwater is added to marine ecosystems. Along the Northeast U.S., salinity variability on the shelf is linked to freshwater input from the Arctic and melting of sea ice.

Altered freshwater systems, due to increased air temperatures and changes in the timing, amount and type (i.e. rain vs. snow) of precipitation, are a major climate induced ecosystem concern for the California Current Ecosystem. The focus is on anadramous fish such as salmon that use river systems and coastal regions for habitat. The primary concerns center on altered stream flows and warmer temperatures affecting survival and passage through tributaries, and changes in coastal ocean habitat quality and productivity due to altered freshwater input. Changes to freshwater input are also important in other regions where species depend upon coastal habitat or coastal currents which are influenced by freshwater input.

Ocean acidification, caused by the oceans absorbing large portions of the carbon dioxide that is being released into the atmosphere by human activities, is a major concern for many of the regional ecosystems. Regions of the northern North Pacific Ocean and the Southern Ocean around Antarctica are predicted to be among the first areas to have their surface waters become undersaturated with respect to aragonite, a form of calcium carbonate utilized by some marine organisms, due to ocean acidification. Likely impacts include reduced growth and survival of commercially important shellfish, reduced fitness and abundance of ecologically important prey (e.g. pteropods, euphausiids) of commercial fish species, and direct effects on commercially important fish species and coldwater corals. In tropical and subtropical regions, including the Pacific Islands and the Southeast U.S. Continental Shelf, Gulf of Mexico and U.S. Caribbean, the potential direct effects of ocean acidification on coral reefs is a primary concern. Coral reefs are susceptible to ocean acidification because reef calcification, and hence growth and survival, depends on the saturation state of carbonate minerals in the surface waters.

Bleaching of shallow water corals, caused primarily by high temperature events, is another major climate induced ecosystem concern for the Pacific Island and Southeast U.S. Continental Shelf, Gulf of Mexico and U.S. Caribbean regions and adds to the stress on these corals caused by ocean acidification. When the temperature tolerance of these corals is exceeded, the corals “bleach”, dissociating from the endosymbiotic algae which normally provide corals photosynthetic energy and their color. If the corals are not able to attain new symbiotic algae within the time that their nutritional needs require, bleaching results in death of the corals. Bleaching can also result in increased susceptibility of corals to diseases which may cause mortality. Increases in water temperature associated with global warming and regionally specific climate variations are leading to increased incidences of coral bleaching.

The rate of sea level rise is predicted to increase due to the thermal expansion of the oceans and loss of land ice. Sea level rise is a major climate related ecosystem concern for parts of the Southeastern U.S., northern Gulf of Mexico, and Pacific Islands. Low-lying coastal regions are susceptible to inundation and loss of wetlands, which could lead to the loss of important fishery habitat. Low-lying atolls and islands in the Pacific may be completely submerged by rising sea levels, leading to the loss of important habitat for endangered Hawaiian monk seals, green sea turtles and sea birds. In addition, reef-building corals may be unable to accrete at a sufficient rate to maintain close enough proximity to the surface to sustain their nutritional needs.

Current Activities

In regions where NMFS has management responsibilities, it conducts assessments of living marine resources and their environment through numerous monitoring and research programs. In most cases this includes monitoring the basic environmental parameters that define the fundamental niche of species of interest and monitoring their key population parameters. The primary goal of the monitoring is to supply stock assessment scientists with the requisite data to make stock assessments and projections. Very few of these assessments and projections currently account for the climate impacts on the populations.

Data from many of the observation programs are being integrated to provide a more comprehensive view of the ecosystems and for distribution to constituents (e.g. reports of the status of the California Current, the Ecosystems Considerations chapter of the Alaskan Stock Assessment and Fisheries Evaluation plan, and ecosystem advisories of the northeast U.S. shelf). All regions also have some studies that explore specific environmental mechanisms that influence living marine resources, though these are generally not core programs with dedicated, long-term support. A couple of notable exceptions are the North Pacific Climate Regimes and Ecosystem Productivity (NPCREP) and the Fisheries And The Environment (FATE) programs, though these programs are supported significantly below their planned levels. NPCREP focuses on how changing climate conditions affect the growth, survival, and recruitment of Alaska's fisheries species. FATE is a national program that supports regional studies to develop and evaluate ecological and oceanographic indices to be used to improve fishery stock assessments and advance understanding of marine ecosystem dynamics.

Research Needs

A combination of retrospective, observation, process and modeling studies are required to advance the understanding of the impacts of climate on living marine resources and address the climate induced ecosystem concerns. Undertaking the necessary research will require additional staff and support for the studies.

Retrospective analyses of ecosystem parameters and climate conditions help determine ecosystem responses to past climate changes, shedding light on how ecosystems may respond to future changes. Retrospective analyses are often the initial climate impact research conducted in a region, since they are relatively low-cost, and much has already been done in most regions. However, there are still a lot of data to be analyzed with the development of new retrospective data techniques and in regions where limited resources have hindered progress.

Long term observations of climate influenced environmental variables and biological parameters must be maintained and expanded to document ecological responses to climate variability and change. All regions identify data gaps that must be filled to enable adequate documentation of climate impacts on the ecosystems. Observational needs include continuation of existing observation programs, spatial and/or temporal expansion of many observations to enable the coverage and resolution necessary to document climate impacts, and the development and implementation of new technologies and techniques.

Targeted process studies are required to understand the mechanisms controlling the responses of living marine resources to climate. Dependence on predictions based upon correlations without an understanding of the controlling mechanisms can lead to inaccurate predictions if climate conditions vary from those occurring when the correlations were established. Targeted process studies should include *in situ* and laboratory experimental studies, depending upon the question of concern, and detailed studies of biological processes and their responses to variable forcing.

A wide range of modeling studies are also necessary for NMFS to address the regional climate related ecosystem concerns. These should range from conceptual models to fully developed, coupled climate and ecosystem models and include models of shoreline evolution under higher sea level, habitat models, and a full suite of biological and ecosystem models (ranging from models of the physiological responses of individual species to particular forcing parameters to whole ecosystem models which include environmental forcing). Models help explain how species and ecosystems respond to climate forcing, generate hypotheses that can be tested, provide predictive capability of ecosystem responses to future climate changes, and ultimately provide predictions of the status of specific living marine resources for given climate prediction scenarios.

Climate Information Needs

Climate observations and predictions are necessary for NMFS to address the identified climate induced ecosystem concerns and incorporate climate into its living marine resource management process. Both historical and current climate observations are needed to document how climate has and is changing in particular regions and for comparisons to the local ecosystem changes. The necessary climate observations include both the physical parameters generally associated with a region's climate (e.g. air and ocean temperature, wind, and precipitation) and the ocean's chemical parameters (e.g. salinity, oxygen, nutrients, and carbonate system parameters). These observations are required on scales that are pertinent to ecosystems. Specifically, sea surface and water column profiles of these parameters are necessary and measurements are needed on spatial and temporal scales that capture the variability experienced by organisms. Indices of climate variability and change are useful to quantify the state and tendency of climate forcing and environmental conditions.

Regional climate predictions are essential for including climate in projections of living marine resource status. Regional predictions of how the mean climate will change and how present climate variations will be affected are needed. Climate forecasts should be developed for different climate forcing scenarios and include a measure of uncertainty. These predictions need to include all the important climate observation parameters, physical and chemical. The development of coupled atmosphere-ocean models is necessary for predictions of climate impacts on ocean physical properties, such as temperature, salinity, currents, meso-scale features, stratification, and upwelling, which are important controlling factors on when and where living marine resources can successfully persist. Stream flow and sea level rise projections are important for anadramous fish and coastal habitat concerns.

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Introduction

The United States has extensive living marine resources that are important to its economy, its quality of life and the world's ecosystems. These living marine resources support a $60 billion per year seafood industry and recreational fisheries that annually contribute $12 billion to the economy. These exploited resources and protected species also help attract vast numbers of people to coastal regions for tourism and recreation. In some parts of the country, native peoples are dependent on these same resources for subsistence and for preserving their traditions and culture. To maintain these resources, including the recovery and conservation of protected and endangered marine species, management plans must be implemented that account for the multiple factors affecting the ecosystems.

Climate is one of the most important factors controlling the distributions and abundances of marine organisms and how ecosystems are structured. The climate in a region ultimately controls most of the physical parameters of ecosystems which, to a great extent, determine the basic habitat suitability for marine species. By impacting species' growth rates, reproductive success, and spatial and temporal distributions, the physical parameters have a large impact on the resulting ecosystem structure, function, and productivity. Therefore, if living marine resources are to be adequately managed, climate variations and changes must be understood and considered in the formulation of management strategies. If climate considerations are not incorporated into these plans, we risk implementing management plans that do not account for evolving environmental conditions and thereby risk over- or under-exploitation of harvested resources and similar mismanagement of non-harvested species.

A goal of climate and ecosystem studies is to be able to predict the probable consequences of global climate change on ecological systems and their living resources, and to deliver to managers the knowledge and tools needed to incorporate climate variability into the management plans. This includes recovery plans for overfished and listed (protected) species. NOAA has made large investments directed at understanding the physical climate system and describing the mechanisms that govern climate variability and climate change, especially as related to the ENSO. However, much more needs to be learned about the impacts of climate variability and change on biological components of ecosystems, or the implications of future climate change on coastal and marine ecosystems. We need to better understand the linkages between "physical forcing mechanisms" and "ecosystem response". That understanding can be attained through increased observations, research and modeling of critical biological elements of the ecosystem (productivity, prey resources, predator impacts, trophic interactions, habitat suitability). Doing so will lead to a better understanding of the critical factors that link climate variability and ecosystem response.

Natural variability combines with human influences, including anthropogenic-induced climate change, to create temporally and spatially complex environments for marine populations. Successful management of these populations and their ecosystems requires an evolution from the traditional physics-to-fish correlations to a more mechanistic-based strategy that takes a holistic, integrative ecosystem approach.

This document presents sections for each regional marine ecosystem for which NMFS has living marine resource management responsibilities. Each section identifies the major climate related ecosystem concerns for the region, what NMFS is currently doing in relation to these concerns, and what additional work NMFS must do to adequately address the concerns to support effective management. In addition, the sections identify the climate information that will be required for this work. The major climate related concerns identified for the different regional ecosystems are listed in Figure 1. While the specifics of the climate concerns differ between regions, there are common issues that reflect closely the climate issues identified in the NOAA program planning process. These include climate impacts on ecosystem productivity, phenology and species distributions; the impacts of the loss of sea ice on polar, sub-polar, and cold temperate ecosystems; altered freshwater systems; ocean acidification; coral bleaching; and ecological effects of sea level rise. For each of these topics climate changes have had major impacts on the living marine resources, as is discussed briefly below.

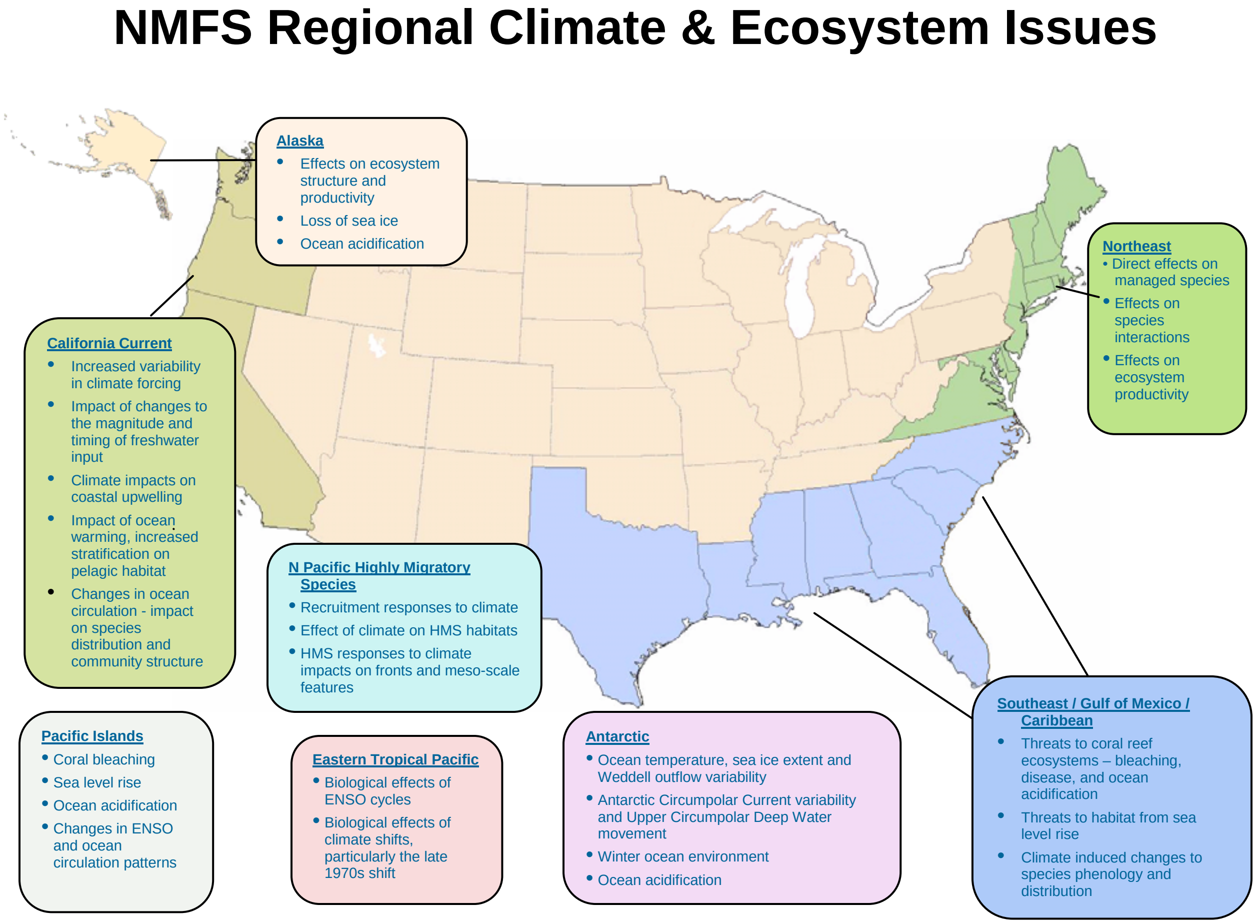

Figure 1. The major climate related ecosystem concerns for the regional marine ecosystems for which NMFS has management responsibilities.

Climate Impacts on Ecosystem Productivity, Phenology and Species Distributions

Modifications to ecosystem productivity, phenology and species distributions often occur in response to altered physical forcing due to climate change. These changes may occur on timescales ranging from seasonal to multi-decadal or longer. Depending upon the duration and magnitude of the climate change, species may persevere through periods of adverse conditions, temporarily shift their distributions or behaviors, or modify their ranges, behaviors and movements over the long term. At the extreme, species may be extirpated from whole regions and potentially become extinct.

Climate directly impacts regional temperature, wind and precipitation patterns. These physical changes may alter the habitat suitability for species directly or indirectly. Examples of direct effects on species include species responses to changes in temperature due to their physiological tolerances. Many marine fish species have been observed to shift their distributions poleward in response to warming waters (Murawski, 1993; Parker and Dixon, 1998; Perry et al., 2005; Mueter and Litzow, 2008) and distributions of Atlantic surfclams have apparently shifted to deeper, cooler water in response to increased coastal temperatures (Weinberg, 2005). Similarly, the Alaskan snow crab distribution has receded northward with the warming of the eastern Bering Sea (Orensanz et al., 2005). As species' distributions shift, the species composition of biological communities are altered with new predator-prey (or host-parasite) relationships formed and others disappearing, stabilizing or destabilizing existing food webs. This in turn can affect the seasonal distribution of apex predators such as whales and pinnipeds (Grebmeier et al., 2006).

Changes in temperature, wind and precipitation patterns can affect ocean circulation, thermal energy distribution, ecosystem productivity and structure, and subsequent habitat suitability for species. An example of this is the timing and strength of seasonal upwelling along the Pacific coast of North America. In 2005 the transition to upwelling favorable conditions in the northern California Current ecosystem was delayed by 2-3 months (Schwing et al., 2006). This delay had severe consequences for many components of the ecosystem, including changes in distributions, abundances and recruitment of many pelagic nekton species (Brodeur et al., 2006), shifts in California sea lion foraging strategies (Weise et al., 2006), and complete breeding failure of a dominant planktivorous marine bird (Sydeman et al., 2006). Similarly, El Niño events cause large ecosystem shifts on multi-year timescales, impacting ocean productivity and population distributions along the U.S. west coast (Pearcy and Schoener, 1987). Overall productivity is reduced during these events and individual species show marked responses. For example, market squid undergo severe population declines during El Niño events, California sea lions have greatly decreased pup production, rockfish show large reductions in reproductive success, and the abundance and distribution of Pacific hake are impacted.

By changing the seasonal timing of certain temperature, current, and stratification patterns in a region, the phenology of the populations that inhabit the region can be affected. Phenology refers to the timing of recurring natural phenomena, particularly ones that occur on an annual cycle. For marine ecosystems the timing and magnitude of primary production can be affected, thus impacting the productivity of the entire ecosystem. Changes in timing and magnitude of primary production can also affect population processes of individual stocks (Friedland et al., 2008). In addition, the timing and location of reproduction by organisms and the migration dates and routes of organisms may change. These temporal changes have large impacts on living marine resource populations and their management.

On decadal time scales, changes in climate forcing have been observed to have large impacts on the productivity of marine ecosystems. These shifts have been referred to as regime or phase shifts since the dominant species and productivity levels markedly change. Large-scale variations in climate forcing have been observed in the Pacific and Atlantic Oceans. In the Pacific, changes such as the decadal shifts in the California Current and Alaska Current ecosystems between warm regimes and cool regimes are a reflection of changes in the ocean circulation and are indicated by climate patterns such as the Pacific Decadal Oscillation (Mantua et al., 1997) or the Arctic Oscillation (Overland and Stabeno, 2004). These oscillations are linked to large-scale shifts in ocean conditions of the North Pacific. Changes in species abundances, such as changes in the composition of zooplankton, survival of Pacific salmon, the dominance of sardines versus anchovies in the California Current ecosystem, and the dominance of groundfish (gadids) versus crustaceans (shrimp and crab) in the Gulf of Alaska ecosystem, are associated with decadal changes in ocean climate (Francis and Hare, 1994; Anderson and Piatt, 1999; Benson and Trites, 2002; Chavez et al., 2003; Peterson and Schwing, 2003). The collapse of the California sardine fishery in the 1940s, which caused large economic and social impacts, was partially caused by a shift to cooler ocean conditions and resulting changes in the ecosystem structure. At that time, the fishery management community was not aware of these affects of climate change on the ecosystem.

In the Atlantic, the impact of the North Atlantic Oscillation (NAO), a measure of the atmospheric pressure difference between the subtropical high and the Icelandic low, on marine populations depends upon how the NAO affects local conditions and their relation to the preferences of the populations (Drinkwater et al., 2003). For example, the NAO has opposite effects on cod recruitment in parts of the western and the eastern Atlantic due to its opposite effects on temperatures in the two regions. Climate changes are believed to have contributed to the collapse of the northern cod stock off southern Labrador and northeastern Newfoundland in the 1990s (Drinkwater, 2002). While overfishing is believed to be the main cause of the cod decline, environmental conditions appear to have contributed to the decline of the cod stock by decreasing growth rates of the fish. The fisheries management did not take the variable environmental conditions into account, and the stocks were depleted to extremely low levels. To date, these stocks show little evidence of recovery. The impact of the Atlantic Multidecadal Oscillation (AMO), another source of climate variability in the Atlantic, are just beginning to be understood (Kerr 2005). The AMO is a 60-80 year cycle expressed primarily as variability in sea surface temperature. Variability in the AMO has been linked to precipitation patterns in Europe and North America and hurricane activity in the Atlantic. The broader ecosystem effects are largely unknown as are the interactions between the AMO and long-term trends in temperature resulting from climate change.

Loss of Sea Ice

Warming temperatures and decreases in sea ice are impacting marine ecosystems in polar, sub-polar, and cold-temperate regions. Summertime Arctic sea ice coverage has been declining since the 1970s and declined to unprecedented low levels during the summer of 2007. The Arctic Ocean may become seasonally ice-free by 2030 (Stroeve et al., 2008). Concurrently, the Bering Sea is undergoing a loss of sea ice and northward biogeographical shift in response to changing climate conditions, with the northern regions shifting from arctic to subarctic conditions (Schumacher et al., 2003; Overland and Stabeno, 2004; Grebmeier et al., 2006; Stabeno et al., 2006; Mueter and Litzow, 2008). The loss of sea ice in the subarctic and arctic has large impacts on the structure of these ecosystems and could result in the reproductive failure and ultimate extinction of some protected species of pinnipeds and polar bears. Not only does it reduce the amount of ice available to ice dependent species (e.g. ribbon, bearded, spotted and ringed seals, polar bear and walrus), it also changes the water column temperature and stratification, the timing and intensity of phytoplankton blooms, and the proportion of pelagic production that becomes available to the benthos. The benthic community includes commercially important flatfish and crab populations (Hunt et al., 2002) and food for many pelagic fish and whale predators. It will change the distribution of preferred habitat by species and may force fishers to expend more effort for the same level of catch. In some regions around Antarctica temperatures have increased, sea ice has declined and krill density has decreased substantially (Hewitt and Linen Lowe, 2000; Smith and Stammerjohn, 2001; Atkinson et al., 2004). While ice dependent species in both polar regions will be negatively impacted by reductions in sea ice, other species whose distributions are limited by sea ice may be able to take advantage of the changing conditions.

In cold-temperate regions, such as the Northeast shelf, freshwater input in the Arctic is responsible for driving salinity patterns through the entire region (Greene and Pershing, 2006). The less saline water enters the Labrador Coastal Current system (Loder et al., 1998) and flows around Newfoundland, down the Scotian Shelf, around the Gulf of Maine and Georges Bank and then through the Mid-Atlantic shelf (Mountain 2004). This large-scale forcing has been linked to changes in zooplankton community structure (Kane 2007) and links to higher trophic levels are being investigated. The effect of changes in sea ice on marine ecosystems illustrates that climate change will have local and remote impacts on regional ecosystems and understanding the linkages between ecosystems will be critical for evaluating both categories of impacts.

Altered Freshwater Systems

Climate change will affect freshwater flows to coastal systems in much of the continental U.S. This will modify the productivity of coastal ecosystems and fish species that use these nearshore environments and may lead to shifts in the trophic structure of marine ecosystems and the abundance and productivity of marine fish species humans depend on. Freshwater systems are intimately linked to living marine resources through the water cycle, flows of water and nutrients from terrestrial to marine ecosystems, and the migrations of anadromous and catadromous fishes that transfer biomass and nutrients between the two environments. Climate change may result in changes in the timing and volume of river flows, thereby influencing the survival of fishes that require these habitats for spawning and rearing (Crozier and Zabel, 2006; Beechie et al., 2006). Increased water temperature from a warmer climate and altered stream flows may impact anadromous fishes and other aquatic species by reducing available habitat, increasing competition with other species, restricting river migration corridors, and causing changes in food supply. At the same time, human population growth will increase demands for freshwater that could exacerbate any flow reductions caused by climate change. Many coastal regions are structured by near-shore buoyancy driven (freshwater) currents and changes in freshwater flow will also affect these coastal regions. For example, some marine fish species may have evolved to have their larvae take advantage of currents to transport them to favorable nursery areas (e.g. Walleye pollock in the Gulf of Alaska). Changes in the timing and magnitude of freshwater delivery to the oceans will change the seasonal transport by currents in these regions.

Ocean Acidification

Changes in the chemical composition of the ocean are occurring due to the oceans absorbing large portions of the carbon dioxide that is released into the atmosphere by human activities. This is causing ocean chemistry to change to a state that has not been present for hundreds of thousands of years (Feely et al., 2004; Sabine et al., 2004; Flannery, 2006). As the oceans absorb carbon dioxide, chemical reactions in the oceans result in increased concentrations of hydrogen ions (higher acidity, lower pH) and decreased availability of calcium carbonate; hence the term ocean acidification has been used to describe this process. This shifting of the carbonate equilibrium of the oceans, making carbonate and calcium ions less available, may be harmful to marine organisms that make structures out of calcium carbonate (Kleypas et al., 2006). These organisms include shallow and deep water corals, calcifying plankton, mollusks, echinoderms, crustaceans and many other organisms, including many of our nation's most valuable fishery resource species. Continued increases in carbon dioxide could decrease the fitness of marine calcifiers, as the calcification rates of some organisms have been shown to decrease under increasing carbon dioxide concentrations (Langdon and Atkinson, 2005). However, the cacification rates of other organisms actually appear to increase as carbon dioxide levels increase (Iglesias-Rodriguez et al., 2008). Changing calcification rates will have impacts on marine calcifiers and the organisms that are dependent upon them for food or habitat. Ocean acidification has likely played a role in all major mass extinctions of the Scleractinia, the deep-sea cold-water corals that are important as biodiversity hotspots by providing habitat for deep-sea organisms (Turley et al., 2007). Increases in acidity also has the potential to affect a number of key biological processes in non-calcifying organisms such as reduction in photosynthesis, availability of nutrients to phytoplankton, the bioavailability of marine toxins to bacteria and phytoplankton, internal carbon dioxide concentrations of marine animals and reduced demersal egg adhesion or fertilization success of eggs broadcast into the ocean (UK Royal Society, 2005). The numerous pathways for effects (both direct and indirect) imply that ocean acidification will impact many marine species over wide geographic areas.

Coral Bleaching

Coral bleaching is another marine ecosystem phenomenon for which climate plays an important role. Coral reefs support more species per unit area than any other marine environment. However, shallow water reefs are very sensitive to elevated sea surface temperature as reef building corals are thought to live near their thermal maxima. When their temperature tolerance is exceeded, the corals "bleach", dissociating from the endosymbiotic algae which normally provide corals photosynthetic energy and their color. If the corals are not able to attain new symbiotic algae in the time period that their nutritional needs require, weeks to sometimes months, the bleaching of the reef results in the mortality of the affected coral. Widespread bleaching events are primarily caused by extended periods of heightened temperatures. There has been a considerable increase in the number of mass bleaching events in recent years, including the 1998 event where an estimated 16% of the world's area of coral reefs was severely damaged (Wilkinson, 2004) and a major bleaching event in the Caribbean Sea in 2005. Comparisons of expected increases in sea surface temperatures with calculated bleaching thresholds suggest that mass bleaching events are likely to become more frequent and severe (Hoegh-Guldberg, 1999; Marshall and Schuttenberg, 2006). This will have significant, negative impacts on coral survival and on the multitude of species that utilize the reefs for food and shelter. It has been predicted that with increasing ocean temperatures, mass bleaching episodes will continue to increase in frequency and severity to the point of coral extinction (Hoegh-Guldberg, 1999). An alternative view suggests that the coral/algal symbiosis is flexible and adaptable and that corals that recover from bleaching are likely to be more resistant to future bleaching via association with more heat-tolerant strains of symbionts (Baker et al., 2004). Also, as ocean temperatures increase, areas formerly too cold for coral may become optimal for coral and thus provide new areas for coral communities to become established.

Sea Level Rise

Climate change also affects coastal marine ecosystems through changing sea levels. Global sea level rose 0.1-0.2 m over the 20th century. There is a strong likelihood of continued sea level rise due to thermal expansion of the oceans and loss of land ice, with the projected range of global average sea level rise from 1980-1999 to 2090-2099 being 0.18-0.59 m (IPCC, 2007). Rising sea level has consequences for coastal regions due to its potential to alter habitat and ecosystems in these regions (Scavia et al., 2002). As a result of sea level rise, coastal wetlands and shallow water habitats are exposed to increases in water depth, salinity, wave action and storm surges. This can have severe consequences for organisms that inhabit these regions for all or part of their life cycles if there is insufficient new habitat created as water levels rise. Areas such as low-lying islands that could be submerged and areas with extensive human infrastructure that will prevent landward migration of coastal ecosystems are particularly at risk, as some coastal habitats could be totally lost in these regions. Areas that are subsiding are also especially at risk due to the very rapid local rises in sea level they will experience.

Summary

All of these climate variations and changes will continue to have large impacts on marine ecosystems, as abiotic oceanic conditions transition to states that may not have existed for thousands of years. Developing the ability to predict and ameliorate the ecological consequences of these events and long term changes is imperative in order to support effective management. We must make substantial and immediate investments in marine climate change research to enable informed decisions by resource managers and society to ensure the future utility and enjoyment of coastal and marine ecosystems under changing climate conditions. The research needs identified in the following regional sections can guide the directions of that investment.

References

Anderson, P. J., and J. F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. *Mar. Ecol. Prog. Ser.* 189: 117-123.

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.

Baker, A. C., C. J. Starger, T. R. McClanahan, and P. W. Glynn. 2004. Corals' adaptive response to climate change: Shifting to new algal symbionts may safeguard devastated reefs from extinction. *Nature* 430: 741.

Beechie, T. J., M. Ruckelshaus, E. Buhle, A. Fullerton, and L. Holsinger. 2006. Hydrologic regime and the conservation of salmon life history diversity. *Biological Conservation* 130(4): 560-572.

Benson, A. J., and A. W. Trites. 2002. Ecological effects of regime shifts in the Bering Sea and eastern North Pacific Ocean. *Fish and Fisheries* 3: 95-113.

Brodeur, F. D., S. Ralston, R. L. Emmett, M. Trudel, T. D. Auth, and A. J. Phillips. 2006. Anomalous pelagic nekton abundance, distribution, and apparent recruitment in the northern California Current in 2004 and 2005. *Geophys. Res. Lett.* 33: L22S08, doi:10.1029/2006GL026614.

Chavez, F. P., J. Ryan, S. E. Lluch-Cota, and M. Ñiquen C. 2003. From anchovies to sardines and back: Multidecadal change in the Pacific Ocean. *Science* 299: 217-221.

Crozier, L. G., and R. W. Zabel. 2006. Climate impacts at multiple scales: evidence for differential population responses in juvenile Chinook salmon. *J. Animal Ecolog*y 75: 1100-1109.

Drinkwater, K. F. 2002. A review of the role of climate variability in the decline of northern cod. *Amer. Fish. Soc. Symp.* 32: 113-130.

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 Impacts, Am. Geophys. Union, *Geophys. Mono.* 134: 211-234.

Feely, R. A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, and F. J. Millero. 2004. Impact of anthropogenic CO_2 on the $CaCO_3$ system of the oceans. *Science* 305: 362-366.

Flannery, T. F. 2006. The Weather Makers: How man is changing the climate and what it means for life on earth. Atlantic Monthly Press, 357p.

Francis, R. C., and S. R. Hare. 1994. Decadal-scale regime shifts in the large marine ecosystems of the Northeast Pacific: A case for historical science. *Fish. Oceanogr.* 3: 279-291.

Friedland, K. D., J. A. Hare, G. B. Wood, L. A. Col, L. J. Buckley, D. G. Mountain, J. Kane, J. Brodziak, R. G. Lough, and C. H. Pilskaln. 2008. Does the fall phytoplankton bloom control recruitment of Georges Bank haddock, *Melanogrammus aeglefinus*, through parental condition? *Canadian Journal of Fisheries and Aquatic Sciences.* 65: 1076-1086.

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.

Greene, C. H., and A. J. Pershing. 2007. Climate drives sea change. *Science* 315: 1084 - 1085

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.

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

Hunt, G. L., Jr., P. J. Stabeno, G. Walters, E. Sinclair, R. D. Brodeur, J. M. Napp, and N. A. Bond. 2002. Climate change and control of the southeastern Bering Sea pelagic ecosystem. *Deep-Sea Res. II*, 49: 5821-5853.

Inglesias-Rodriguez, M. D., P. R. Halloran, R. E. M. Rickaby, I. R. Hall, E. Colmenero-Hidalgo, J. R. Gittins, D. R. H. Green, T. Tyrrell, S. J. Gibbs, P. von Dassow, E. Rehm, E. V. Armbrust, and K. P. Boessenkool. 2008. Phytoplankton calcification in a high-CO_2 world. *Science* 320: 336-340.

Intergovernmental Panel on Climate Change (IPCC). 2007. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change* [Solomon, S., D. Qin, M. Manning, M. Marquis, K. Averyt, M. M. B. Tignor, H. L. Miller, Jr., and Z. Chen (eds.)]. 996pp.

Kane, J. 2007. Zooplankton abundance trends on Georges Bank, 1977–2004. *ICES Journal of Marine Science* 64: 909–919.

Kerr, R. A. 2005. Atlantic climate pacemaker for millennia past, decades hence? *Science* 309: 43-44.

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, LF, sponsored by NSF, NOAA, and the U.S. Geological Survey, 88pp.

Langdon, C., and M. J. Atkinson. 2005. Effect of elevated pCO_2 on photosynthesis and clacification of corals and interactions with seasonal change in temperature/irradiance and nutrient enrichment. *J. Geophys. Res.* 110: C09S07, doi:10.1029/2004JC002576.

Loder, J. W., B. Petrie and G. Gawarkiewicz, 1998. The coastal ocean off northeastern North America: A large-scale view. In: The Sea, **11**, A. Robinson and K. Brink, eds., 105-133.

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.

Marshall, P. A., and H. Z. Schuttenberg. 2006. A Reef Manager's Guide to Coral Bleaching. Great Barrier Reef Marine Park Authority, Australia (ISBN 1-876945-40-0).

Mountain, D. G. 2004. Variability of the water properties in NAFO subareas 5 and 6 during the 1990s . *Journal of Northwest Atlantic Fishery Science* 34: 103-112 doi:10.2960/J.v34.m475

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

Mueter F. J., and M. A. Litzow. 2008. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecological Applications*. 18(2): 309-320.

Orensanz, J., B. Ernst, D. A. Armstrong, P. Stabeno, and P. Livingston. 2005. Contraction of the geographic range of distribution of snow crab (*Chionoecetes opilio*) in the eastern Bering Sea: An environmental ratchet? *Rep. CA Coop. Ocean. Fish. Invest.* 45: 65-79.

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.

Parker, R. O., Jr., and R. L. Dixon. 1998. Changes in a North Carolina reef fish community after 15 years of intense fishing – global warming implications. *Trans. Am. Fish. Soc.* 127: 908-920.

Pearcy, W. G., and A. Schoener. 1987. Changes in the marine biota coincident with the El Niño in the northeastern subarctic Pacific. *J. Geophys. Res.* 92: 14,417-14,428.

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.

Peterson, W. T., and F. B. Schwing. 2003. A new climate regime in northeast pacific ecosystems. *Geophys. Res. Lett.* 30(17): 1896, doi:10.1029/2003GL017528.

Sabine, C. L., R. A. Feely, N. Gruber, R. M. Rey, K. Lee, J. L. Bullister, R. Wannikof, C. S. Wong, D. W. R. Wallace, B. Tilbrook, F. J. Millero, T.-H. Peng, A. Kozyr, T. Ono, and A. F. Rios. 2004. The oceanic sink for anthropogenic CO_2. *Science* 305: 367-370.

Scavia, D., J. C. Field, D. F. Boesch, R. W. Buddemeier, V. Burkett, D. R. Cayan, M. Fogarty, M. A. Harwell. R. W. Howarth, C. Mason, D. J. Reed, T. C. Royer, A. H. Sallenger, and J. G. Titus. 2002. Climate change impacts on U.S. coastal and marine ecosystems. *Estuaries* 25: 149-164.

Schumacher, J. D., N. A. Bond, R. D. Brodeur, P. A. Livingston, J. M. Napp, and P. J. Stabeno. 2003. Climate change in the southeastern Bering Sea and someconsequences for biota. In: Large Marine Ecosystems of the World – Trends in Exploitation, Protection and Research, Hempel, G. and K. Sherman (Eds.), pp. 17-40.

Schwing, F. B., N. A. Bond, S. J. Bograd, T. Mitchell, M. A. Alexander, and N. Mantua. 2006. Delayed coastal upwelling along the U.S. West Coast in 2005: A historical perspective. *Geophys. Res. Lett.* 33: L22S01, doi:10.1029/2006GL026911.

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.

Stabeno, P. J., G. L. Hunt, Jr., J. M. Napp, and J. D. Schumacher. 2006. Physical forcing of ecosystem dynamics on the Bering Sea shelf. In: *The Sea*, Robinson, A. R. and K. H. Brink (Eds.), 14: 1177-1212.

Stroeve, J., M. Serreze, S. Drobot, S. Gearheard, M. Holland, J. Maslanik, W. Meier, and T. Scambos. 2008. Arctic sea ice extent plummets in 2007. *EOS, Trans. Am. Geophys. Union* 89: 13-14.

Sydeman, W. J., R. W. Bradley, P. Warzybok, C. L. Abraham, J. Jahncke, K. D. Hyrenbach, V. Kousky, J. M. Hipfner, and M. D. Ohman. 2006. Plantivorous auklet (*Ptychoramphus aleuticus*) responses to the anomaly of 2005 in the California Current. *Geophys. Res. Lett.* 33: L22S09, doi:10.1029/2006GL026736.

Turley, C. M., J. M. Roberts and J. M Guinotte. 2007. Corals in deep-water: will the unseen hand of ocean acidification destroy cold-water ecosystems? *Coral Reefs* 26: 445-448.

UK Royal Society. 2005. Ocean acidification due to increasing atmospheric carbon dioxide. The Royal Society, pp. 57.

Weinberg, J. R. 2005. Bathymetric shift in the distribution of Atlantic surfclams: response to warmer ocean temperature. *ICES J. Mar. Sci.* 62: 1444-1453.

Weise, M. J., D. P. Costa, and R. M. Kudela. 2006. At-sea movement and diving behavior of male California sea lion (*Zalophus californianus*) during 2004 and 2005. *Geophys. Res. Lett.* 33: L22S10, doi:10.1029/2006GL027113.

Wilkinson, C. 2004. *Status of coral reefs of the world: 2004. Vol. 1.* Australian Institute of Marine Science. Townsville, Australia. 301pp.

Northeast U.S. Continental Shelf

Authors:
Jonathan Hare and Maureen Taylor
(Northeast Fisheries Science Center)

Introduction

The northeast U.S. continental shelf ecosystem extends from Cape Hatteras, North Carolina to Nova Scotia and includes the Middle Atlantic Bight, the southern New England shelf, Georges Bank, and the Gulf of Maine (Figure 1). The ecosystem spans a large climate gradient from south to north, including a 10-15°C temperature gradient in winter and a 4-5 psu salinity gradient year round. The ecosystem also experiences a large seasonal range of temperature from approximately 5-10°C in the northern Gulf of Maine to near 20°C along the Mid-Atlantic coast (Mountain and Holzwarth, 1989). There are a number of large estuarine systems along the coast through which fresh waters flow onto the shelf, including Chesapeake Bay, the largest estuary in the United States. At the offshore edge of the shelf, a front separates shelf water from slope water. The fresher water along the inner boundary of the shelf and the more saline slope water at the outer boundary creates a cross-shelf salinity gradient of ~5-6 psu.

In addition to large environmental gradients, the northeast U.S. shelf has a variety of pelagic and benthic habitats (Stevenson et al., 2003). A number of pelagic habitats are defined by discrete water masses and water mass boundaries (Mountain, 2000; Waring et al., 2001). The shelf bottom has areas of sand, mud, and gravel bottom that create a mosaic of habitat types. The estuarine systems at the inner boundary of the shelf provide numerous habitats ranging in salinity from fresh to marine. A number of fish species use these habitats as nurseries (Able and Fahay, 1998). At the offshore edge of the shelf, there are several canyons and a variety of bottom types, which provide a complex set of habitats for fish species (Grimes et al., 1986; Cooper et al., 1987).

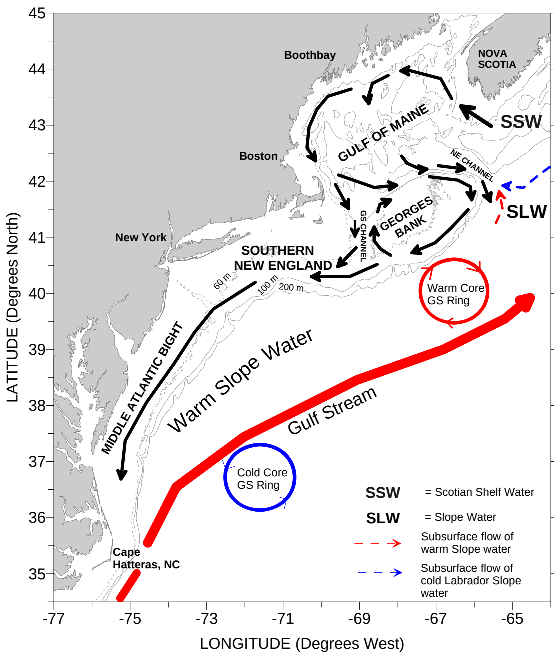

Figure 1. Generalized circulation patterns of the Northeast U.S. Continental Shelf ecosystem.

These large temporal and spatial environmental gradients and the diversity of habitats enable a wide variety of species to inhabit the ecosystem as year round and seasonal residents. Approximately 1,000 fish species occur in marine waters from Cape Hatteras, North Carolina to Greenland, including coastal, shelf, and deep-sea habitats (Fahay, 2007). In an exhaustive study of nearshore fishes of the northeast U.S. shelf, Able and Fahay (1998) found that 70% were transient, indicating the importance of seasonal and life history migrations in the region's fish fauna. A number of marine mammal (~30) and sea turtle (~6) species

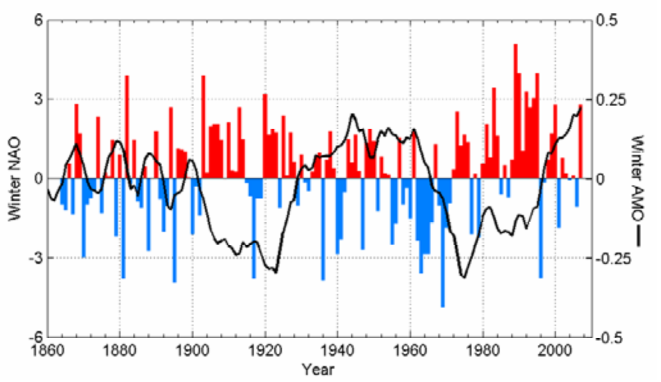

Figure 2. Winter NAO (bars) and winter AMO (line). Data from NAO winter index downloaded from http://www.cgd.ucar.edu /cas/ jhurrell/indices.html. AMO values downloaded from http://www.cdc.noaa.gov/Timeseries/AMO/ and smoothed with a 5-yr running average.

occur in the ecosystem; many of these species are migratory, but some are year round residents. In addition, there are about 130 species of marine decapod crustaceans inhabit the northeast U.S. continental shelf, with arctic-boreal species representing about 40% and temperate-tropical species representing 60% (Williams, 1984). More than 550 macrobenthic invertebrates are found on the shelf, and faunal composition varies both along-shelf (the boreal-temperate gradient) and across-shelf (the coastal-shelf-slope gradient) (Theroux and Wigley, 1998). Zooplankton communities also vary predictably both along-shelf and cross-shelf with contributions of arctic-boreal species, temperate-tropical species, nearshore species, shelf species, and deep-water species (Cox and Wiebe, 1979; Bourne and Yentsch, 1987).

The climate of the northeast region is influenced by at least two natural climate oscillations: the North Atlantic Oscillation (NAO) and the Atlantic Multidecadal Oscillation (AMO) (Figure 2). The NAO is the dominant mode of winter climate variability in the North Atlantic region and is a large-scale seesaw in atmospheric mass between the subtropical high and the Icelandic low (Hurrell et al., 2003). The periodicity of the NAO is several years, and during positive periods of the NAO (stronger subtropical high and deeper Icelandic low), the eastern U.S. experiences mild and wet winter conditions; the opposite holds for negative periods of the NAO (weaker subtropical high and Icelandic low). The AMO describes variability in sea surface temperature in the North Atlantic Ocean with a longer periodicity (65-80 yrs) than the NAO and has an amplitude of about 0.5°C (Kerr, 2000). While in the positive phase (e.g., 1930-1965), rainfall over the eastern U.S. was lower and while in the negative phase (e.g., 1965-1995) rainfall was higher (Enfield et al., 2001). The AMO seems to be switching into its positive phase with warmer ocean temperatures and decreased rainfall (Kerr, 2005). Other climate oscillations also affect the northeast U.S. shelf, such as the El Niño-Southern Oscillation (ENSO) which can influence precipitation and freshwater input along the

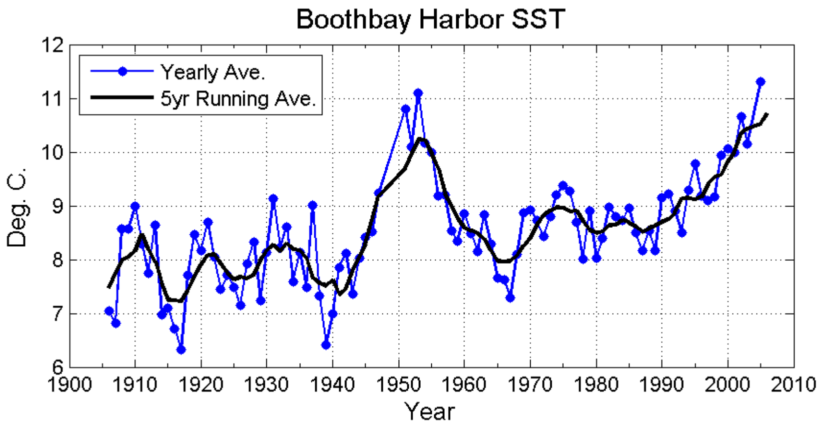

Figure 3. Time series of sea surface temperature measured at Boothbay Harbor Maine and archived by the Maine Department of Marine Research

east coast (Wu et al., 2005). While the magnitude of environmental variability related to these other oscillations is less than that associated with NAO and AMO, it is important to recognize that a complex interaction of climate-scale forcing drives environmental variability along the shelf.

The northeast region has experienced general warming since the 1970's, about 0.5^{o}C per decade (Mountain, 2004). The time series of coastal sea surface temperature measured at Boothbay Harbor, Maine (Figure 3) shows that nearshore temperature has generally increased since the 1980s. The high temperatures in the 1940's and 50's may be related to the positive phase of the AMO. If the current trend continues, water temperatures will be higher at Boothbay than at any other point during the 100-year record. Consistent with the coastal observations, Mountain (2003) documented that the shelf water of the Mid-Atlantic Bight was ~1°C warmer during 1990s relative to the previous decadal average. Further, Friedland and Hare (2007) found that not only have the sea surface temperatures of the northwest Atlantic increased, but the seasonal range of surface temperature also has increased, which may have equally important consequences for the living marine resources of the region as the general warming trend.

Climate Induced Ecosystem Concerns

On the northeast U.S. continental shelf, a number of exploited species are over-fished and a number of protected species remain endangered. Many current management plans strive to rebuild fisheries to sustainable levels and to return protected species from their endangered or threatened status. However, these management strategies assume that the ecosystems on which these species depend are at equilibrium – variable but with no long-term trends. With documented increases in temperature and further increases forecast for the future, it is clear that novel environmental conditions will be experienced in the near future and will continue for decades to come. Thus, the northeast U.S. shelf ecosystem cannot be assumed to be at equilibrium. To be successful, sustainable management will need to consider the implications of these changes for the managed species and the ecosystem as a whole. Understanding these changes and their implications is the overall climate priority of the NEFSC.

To address this priority the capability to couple climate models with various ecological and fisheries models is needed to forecast the combined effect of fishing and climate on exploited populations. These models then could be used as the basis for scientific advice for rebuilding and sustaining the fisheries. Although such coupled climate-fishery forecasts are within reach (Lehodey et al., 2006, Fogarty et al. 2008), a large amount of research will be required to develop and apply these coupled models operationally. To this end, the primary climate concerns are:

I. Direct Effects of Changing Environment on Managed Species
II. Effects of Changing Environment on Species Interactions
III. Effects of Climate Change on Ecosystem Productivity

These three concerns have a common goal: to forecast the effects of climate change on fisheries and protected species and incorporate these forecasts into the advice provided to managers. Such forecasts can predict chilling results, such as the dramatic decrease or extirpation of cod from the North Sea (Clark et al., 2003) and Georges Bank (Fromhoof et al., 2007). In a more detailed analysis, Fogarty et al. (2008) showed that the yield curves for cod in the Gulf of

Maine differ under different climate scenarios indicating that optimal harvest levels change with changing climate (Figure 4). This work suggests that as waters warm, the maximum sustainable yield of cod in the Gulf of Maine will decrease, as will the fishing mortality required to achieve this maximum yield.

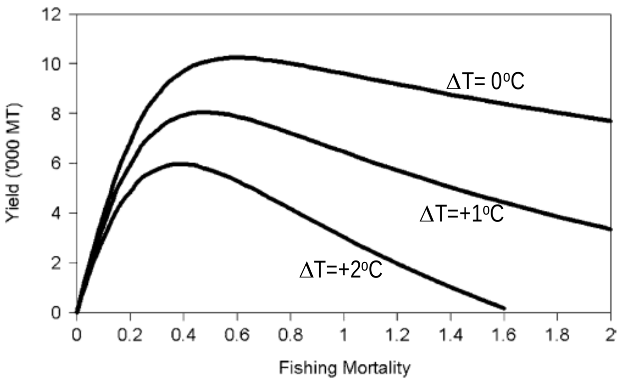

Figure 4. Predicted yield of Atlantic cod from the Gulf of Maine as a function of fishing mortality and changing temperature. The base condition (ΔT= 0°C) represent mean temperatures during 1982-2003. The other two conditions (ΔT=+1°C, ΔT=+2°C) represent temperature increases from the base condition (modified from Fogarty et al. 2008).

The overall goal is a capability to forecast the effect of climate change on fishery and protected species in the northeast U.S. and to incorporate the resulting forecasts into the scientific advice provided to managers. To develop this capability, the mechanistic connections between climate and population biology or ecosystem function need to be established and quantitatively linked within population, ecosystem and climate models. Although understanding and predictive capability can come from correlative analyses alone (MacKenzie and Köster, 2004; Friedland et al. 2008), the emphasis on mechanistic connections comes from the repeated failure of a correlation-only approach (Myers, 1998); studies across the taxonomic spectrum have concluded that climate forecasts of populations and ecosystems need to be based on mechanistic connections regarding the causal links between climate and biology (e.g., Ohman et al., 2004; Lehoydey et al., 2006). To meet this need, the climate-related research priorities of the Northeast Fisheries Science Center (NEFSC) emphasize laboratory and processes-oriented field work, which are required to develop the mechanistic understanding of climate-ecosystem-population links, and the various monitoring and modeling capabilities, which link these mechanisms with population, ecosystem, and climate models.

I. Direct Effects of Changing Environment on Managed Species

Description

All species have a range of environmental parameters in which they can live – defined as the fundamental niche (Hutchinson, 1965). Climate change will result in temporal and spatial shifts in the fundamental niche of a species. In addition, climate change will directly affect population dynamics in many species through direct environmental effects on population vital rates including reproduction, recruitment and survival.

These somewhat abstract concepts have concrete examples from fishery species in the northeast U.S. shelf. Murawski (1993) demonstrated that the distributions of many species on the northeast shelf are affected by temperature. As temperature changes, species distributions will change in response to shifts in the temporal-spatial location of the fundamental niche (also see Mountain, 2000). Many fish species can move in response to changes in environmental conditions, but sessile benthic organisms cannot. Weinberg (2005) documented an offshore shift in the distribution of Atlantic surfclam and related this shift to thermal stress. Individuals did not move, but the population distribution changed as the fundamental niche constricted and mortality exceeded recruitment in the inshore portion of the range. In addition to affecting distribution, the environment can also directly influence population vital rates. Hare and Able (2007) found a close relationship between estuarine temperature and recruitment of Atlantic croaker. During warm winters, estuaries throughout the Middle Atlantic Bight allowed overwinter survival of young-of-the-year croaker, leading to high recruitment, whereas during cold winters, overwinter survival was limited to estuaries in the southern Middle Atlantic Bight resulting in lower recruitment. Similar results have been found for other species in Mid-Atlantic estuaries including striped bass (Hurst and Conover, 1998; Hurst, 2007). The interpretation is that temperature is a component of the fundamental niche and as temperature changes so does the distribution of the niche, as well as population vital rates in different parts of the niche.

Temperature is not the only environmental parameter that will change with changing climate. Precipitation patterns may change, influencing freshwater runoff into coastal areas. Sullivan et al. (2006) showed that American eel ingress into a New Jersey estuary was correlated with local precipitation; the implication is changes in precipitation patterns may have consequences on the number of eels recruiting in a given region. Similarly, changes in wind patterns may affect the transport of marine fish and invertebrate larvae. Friedland et al. (2007) suggested that changes in wind patterns over the Sargasso Sea affect larval transport of American and European eel and may contribute to trends of lower recruitment. As a final example, ocean acidification may affect the ability of organisms to produce carbonate structures (Orr et al., 2005) and calcification rates of many organisms decrease in response to decreased carbonate saturation state even when these states remain > 1 (Feely et al., 2004). The impacts of acidification also may differ among life history stages and initial calcification might be a particularly vulnerable stage (Cohen et al., 2007).

The environment also directly affects the metabolism of marine species. The response of metabolism to temperature and salinity in large part defines the boundaries of the fundamental niche. But the environment also regulates the allocation of energy within the boundaries of the fundamental niche. All species have an optimum temperature, salinity, depth, etc. and at this optimum, a maximum amount of energy is available for growth and reproduction. Similarly, all species have physiological boundaries; environmental conditions where basic metabolic needs cannot be met and survival is not possible. Between these optimums and boundaries, the environment still influences the biology of individuals. For example: growth efficiency (the amount of growth per unit of food consumed) for early stage cod juveniles is highest at 8^{o}C and near zero at 15^{o}C. So to have equal growth, a fish at 15^{o}C would need to consume much more than a fish at 8^{o}C (Peck et al., 2003). Faster growing, larger fish have a lower mortality rate (Anderson, 1988) and produce more and better quality eggs (Trippel and Niel, 2004). Thus, changes in temperature and other environmental parameters can affect growth, reproduction, recruitment, and natural mortality and eventually have an impact on the overall production of the population. The results presented by Fogarty et al. (2008) (Fig. 4) could apply to many, if not most, species in the region.

Current Activities

The NEFSC is monitoring the basic environmental parameters that define the fundamental niche of marine fish species: temperature and salinity. The monitoring programs include approximately 2000 profiles of temperature and salinity per year. Satellites are used to provide high frequency, synoptic measures of surface temperature and chlorophyll distributions. In addition, the NEFSC is actively involved in the two Regional COOS that operate within the Northeast U.S. Continental Shelf: the Northeastern Regional Association of Coastal Ocean Observing Systems (NERACOOS; http://www.neracoos.org/) and the Mid-Atlantic Coastal Ocean Observing Regional Association (MACOORA; http://www.macoora.org/).

The NESFC is also monitoring basic population parameters of a variety of species in the ecosystem. Bottom trawl surveys of demersal and some pelagic species are conducted during the spring and fall. Samples taken during these surveys are used to determine abundance, distribution, growth, age, maturity, sex, and gut contents of a wide variety of fishery species. These surveys and vital statistics form the bases for many of the stock assessments conducted by the NEFSC. Surveys are also made of bivalve species (scallop, clam), apex predators (sharks), and marine mammals. Plankton monitoring occurs across the shelf six times annually; these surveys quantify the abundance and distribution of zooplankton - including the early life stages of fishery species.

Data from these monitoring programs are being integrated to provide a more cohesive view of the ecosystem and to distribute this information to a broader audience. Web-based Ecosystem Advisories are being produced (http://www.nefsc.noaa.gov/omes/OMES/) that present general trends in temperature, primary production and secondary production across the northeast U.S. shelf ecosystem. Monitoring and research information has also been used to develop a descriptive publication for the general public regarding the ecology of the shelf (http://www.nefsc.noaa.gov/ecosystems/Ecosystems.pdf). Finally, presentations are being made to the regional fishery management councils to better inform them about the ecosystem and to lay the foundation for ecosystem approaches to fishery management. The overall purpose of these and other efforts is to present general ecosystem trends on a regular basis to educate scientists, managers, and the public as to the structure and function of the northeast U.S. shelf ecosystem. Data from these monitoring programs also has provided the foundation for much of the research cited above examining links between climate and fisheries on the northeast U.S shelf (e.g., Murawski, 1993; Mountain, 2000; Weinberg, 2005, Fogarty et al. 2008).

Several projects are underway within the northeast U.S. Continental shelf region as part of the NMFS Fisheries and the Environment (FATE) program (http://fate.nmfs.noaa.gov/). These projects explore specific environmental mechanisms that influence fisheries. Environmental indicators are being developed to assist in the sustainable management of living marine resources in a changing climate.

NEFSC scientists have also examined the susceptibility of diadromous species to climate change focusing on interactions between climate and the complex migrations and specialized early life history stages characteristic of these species. American eel spawn in the Sargasso Sea in an area that overlaps the spawning area of the European eel. Both species are in decline due to recent recruitment failures attributed to the effect of changing sea surface temperature and wind conditions in the Sargasso Sea on their leptocephali larvae (Friedland et al., 2007). Atlantic salmon, an endangered resource in the Gulf of Maine, migrates to sea as juveniles and must contend with the match or mismatch between migration timing and the ocean climate conditions affecting their first months at sea (Friedland et al., 2003a; 2003b). In both cases, researchers suspect that population dynamics of these species is being affected by basin-scale climate drivers.

In addition to larger-scale studies examining the interaction between climate, life history stage, and migration, there is also field research underway using acoustic tags to study the short term (within season) movements of fishery species within estuaries (bluefish, weakfish and striped bass) and on the shelf (yellowtail flounder). This novel approach complements traditional tagging projects conducted cooperatively with the region's fishers that include Atlantic cod, haddock, black sea bass and sharks (e.g., Hunt et al., 1998; Kohler et al., 1998). The information on movement is crucial to understanding how individuals move within their fundamental niche and to understanding the environmental conditions associated with and potentially triggering movement. This information could then be used to better quantify the spatial and temporal overlap of predators, prey, and competitors.

Research Needs

- Develop mechanistic understanding regarding the direct effect of environmental variables (e.g., temperature, salinity, currents, acidification) on population vital rates (e.g., recruitment, growth, maturity, fecundity, calcification), species distribution, individual movement, and population spatial structure.
- Develop population and individual "indicator" variables to gauge the response of species to emerging climate patterns with an emphasis on retrospective analyses based on previously collected data and archives of biological samples.
- Incorporate mechanistic understanding into population models and couple these population models with climate models to develop forecasts of the effects of climate change on population dynamics of managed species.

To more fully understand and to be able to forecast the effect of climate change on managed species, mechanistic understanding of the effect of the environment on population vital rates and spatial dynamics is needed. To develop this understanding, coordinated laboratory, field, and modeling efforts are needed. The goal is to quantitatively describe aspects of the fundamental niche of each managed species and then forecast how the spatial and temporal distribution of the niche changes or how production within the niche changes as a result of several climate change scenarios. The approach has been developed for cod and lobster (see Frumhoff et al., 2007; Fogarty et al., 2008) and by NMFS/OAR staff for Atlantic croaker. The specific balance of laboratory, field and modeling work would vary depending on the species of interest and the identified knowledge gaps.

An important step would be retrospective analyses of existing laboratory, monitoring and field studies. There is already a substantial amount of relevant data for many species and the ongoing monitoring programs provide a wealth of data for model development and evaluation. Once data gaps are identified, there will be the need for additional field and laboratory research, but the type and amount varies from species to species. For example, the temporal and spatial distribution of all life stages of Atlantic cod have already been mapped (Fahay et al., 2004) and complex individual based models have been developed based on a combination of field work and laboratory studies (Lough et al., 2005). These data and models could be combined to model the fundamental niche of cod. The next step is coupling these population models with climate models to forecast changes in distribution (see Fogarty et al. 2008). The main limitation is the ability of climate models to forecast environmental conditions in the ocean (see below). For other species, like sea scallops, there is a paucity of basic data regarding the distribution of early life stages relative to the environment and very little laboratory information to define the fundamental niche for any life stage. The limitations here include laboratory and field data in addition to the ability of climate models to forecast environmental conditions in the ocean.

The effect of climate on movement and connectivity in marine populations also needs to be elucidated. There is a large body of work that describes the effect of temperature and salinity on distribution (Murawski, 1993). As temperature changes, distributions will change and there is a need to understand the links between temperature and distribution and then convert this understanding into predictive models. Environment can also affect the timing and magnitude of movements and migrations. Our understanding of movement is much less developed than our understanding of distribution. Most marine species have dispersive early life history stages and movement during these stages is governed by a combination of biological and physical processes (Pineda et al., 2007). For most marine fishery species, movement also occurs during the juvenile and adult life stages. Traditional and acoustic tags have been used to study movement during these stages (see above). Movement, both active and passive over the whole life cycle needs to be considered together. Understanding the cues for spawning and for movement are necessary to evaluate potential changes in spawning distributions, planktonic transport, and juvenile and adult habitat usage. Again, both laboratory and field work is needed to study movement (passive and active) of fishery and protected species. Analyses of previously collected data and of data from ongoing monitoring programs would contribute to the overall effort. These efforts should be within the context of developing mechanistic understanding of the effect of the environment on distribution and movement of resource species with the goal of incorporating this understanding into population models.

Since there are more than 50 managed fishery species that use the northeast U.S. shelf, a productive approach would be to identify "indicator" species that represent certain characteristics of a group of species and then to develop the forecasting models for these select species initially. Such groups could include southern migrants (e.g., Atlantic croaker), cold-water residents (e.g., cod or haddock), nearshore species (e.g., winter flounder), benthic invertebrates (e.g. sea scallop or surfclam). The focus on "indicator species" would provide a range of anticipated responses for the suite of managed species. Once models and forecasts are developed for the "indicator species", work could begin on the other managed species in the system. Further, a process for reviewing and revising forecasts could be established so at some interval (5-10 years) managers could expect an update on the best scientific information available.

Resource Needs

- Increased support for current monitoring programs to collect additional data (e.g., *in situ* primary production, components of the carbonate cycle) to contribute to the development of mechanistic understanding and the operational implementation of coupled environment-population models.
- Staff support for retrospective data-mining activities to analyze all relevant laboratory and field data regarding environment-population links for managed species in the region.
- Targeted lab and field studies aimed at developing and testing mechanistic understanding of the links between environment and populations and for parameterizing linked environment-population models. To conduct the necessary laboratory work, an investment would need to be made in the NEFSC seawater laboratory facilities. Additionally, ship time and equipment would be required for process-oriented field work. Finally, staff would be needed to operate laboratories and conduct field work.
- Synthesis and modeling activities require staff. Activities would need to be coordinated with ongoing monitoring and research activities and with ongoing assessment activities. Interactions with climate models would also need to be developed.

Climate Information Needs

- Standardized hindcasts (past 100 years) of important environmental variables (priority should be given to temperature, salinity, and currents) on standard 3D grid of northeast U.S. shelf ecosystem.
- Standardized forecasts (forward 100 years) of important environmental variables (priority should be given to temperature, salinity, and currents) on standard 3D grid of northeast U.S. shelf ecosystem. Forecasts should be developed for different climate forcing scenarios and should include a measure of uncertainty.
- Ongoing measurement of environmental variables used in a data assimilative approach to update climate forecasts on a regular basis. Measurements would need to include more emphasis on the ocean interior.
- Tools to extract pertinent environmental data from climate model outputs for linking to environment-population models.

II. Effects of Changing Environment on Species Interactions

Description

The fundamental niche describes the environmental boundaries in space and time within which a population can potentially live. As a result of interactions with other species (e.g., predators, competitors, prey), the realized niche is narrower and represents a set of environmental and biological conditions within which a population can sustain itself.

A number of different approaches have been used to examine the effect of environmental change on species interactions, but relatively little work has been done in the northeast U.S. shelf ecosystem. In one of the few ecosystem-specific examples, Manderson et al. (2007) found that predation risk of winter flounder juveniles in estuaries was higher at higher temperatures and higher salinities because of the greater spatial and temporal overlap with predators. Thus, climate related environmental change could increase or decrease predatory interactions and ultimately affect production of winter flounder. Working in the North Sea, another ecosystem at the temperate-boreal boundary, Lynam et al. (2005) proposed that climate variability, specifically the North Atlantic Oscillation, may mediate the competitive interactions between herring larvae and jellyfish, resulting in a cyclic impact on herring recruitment. In another, more distant example, Petersen and Kitchell (2001) used a bioenergetic model to estimate that consumption of predators on juvenile Chinook salmon was higher during warm decades than cold decades and this environment-predation interaction potentially contributed to population variability. In yet another example, Ciannelli et al. (2007) inferred that age-0 cod survival in the Barents Sea was related to the distribution of older cod; as climate affects the distribution of older cod, the pattern of survival of age-0 cod will change resulting in changes in recruitment. These studies indicate that climate can affect the dynamics of species interactions, thereby influencing the temporal and spatial distribution of the realized niche and population production within the niche space.

Since so many of the northeast U.S. shelf fishery species migrate at some portion of the year or during some portion of their life cycle, the changes in the phenology or timing of prey, predators, or competitors could also greatly influence population productivity. A paradigm in recruitment research is the importance of the match of prey production to the spawning time of marine fishes (Cushing, 1990). Platt et al. (2003) found that haddock recruitment on the Scotian Shelf was correlated to the timing of the spring bloom, with high recruitment in years with an earlier bloom. The inference is that earlier blooms provide a better match of prey production for larval haddock, which results in higher recruitment. Recent work on the northeast US shelf (Friedland et al., 2008) has found that timing of the spring bloom is not related to recruitment, but the magnitude of the fall bloom is. This dichotomy indicates that the interplay of climate and species interactions is likely system and species specific, making the work of forecasting species response to climate change a challenging task.

Current Activities

The NEFSC Food Web Dynamics program samples gut contents of fishes collected in the Bottom Trawl Survey. This program has been in operation since 1963 and has undergone several major changes in sampling protocols. The food habits database contains diet information from more than 500,000 stomach samples from over 100 species. These data allow predatory and potential competitive interactions to be identified. The other monitoring data described above also allows for spatial overlaps among species to be documented and related to environmental conditions.

In addition, NEFSC scientists have been involved in the U.S. GLOBEC Georges Bank Program, a multi-disciplinary, multi-year oceanographic effort. The proximate goal is to understand the population dynamics of key species on the Bank: two important fishery species (cod and haddock) and several zooplankton species (*Calanus finmarchicus* and *Pseudocalanus* spp.). The program emphasizes the coupling of these species to the physical environment and the links between these species as predator and prey (see Buckley and Durbin, 2006). The ultimate goal is to be able to predict changes in the distribution and abundance of these species as a result of changes in their physical and biotic environment, as well as to anticipate how their populations will respond to climate change. The Georges Bank program is in its final stage of synthesis and the U.S. GLOBEC Program is preparing for Pan-regional synthesis, with the goal of comparing among marine ecosystems.

Research Needs

- Develop mechanistic understanding of the effect of environmental variables (e.g., temperature, salinity, currents) on species interactions (e.g., predation, competition, phenology).
- Develop multi-species environmentally explicit population models
- Couple environment-multispecies models with climate models to develop forecasts of the effects of climate change on population dynamics of managed species

Quantifying species interactions is a difficult task. Predatory relationships are relatively straightforward to document, but the ability of predators to select and switch among prey makes modeling the effect of predation on population dynamics more difficult. Identifying competitive interactions is even more challenging: species must vie for the same resource and this resource must be limiting to one or both species. A combination of laboratory and field studies is necessary to understand and develop models of predatory and competitive interactions. Such studies must be carefully designed, because the results from short-term experiments do not necessarily match those of longer-term experiments and field observations (e.g., Buckel et al., 1995).

In addition to understanding and quantifying species interactions, there is a need to examine the role of the environment in mediating these interactions. Quantifying environmental effects on predatory and competitive processes is important – for example the effect of temperature on consumption, assimilation, and activity (Claireaux et al., 1995). Understanding the effect of the environment on the distribution and production of species in time and space is also important. For example, changing temperature and salinity may change the spatial overlap of predators and prey (Manderson, 2007) or may change the temporal overlap of predators and prey (Juanes and Conover, 1995), thereby influencing the predatory and competitive interactions. The goal is to develop mechanistic understanding, and both laboratory and field research are needed to achieve this goal. Again, the specific needs will depend on the species.

Of equal importance is developing the population models that include mechanistic understanding of the effect of the environment on species interactions. One approach is to use discrete-time predator prey models (e.g. Collie and Spencer, 1994) but to include the climate effects through individual species models that include direct effects (described in Section I). Alternatively, individual-based models can be used to examine the effect of different environmental conditions on predator-prey interactions – such an effort could build upon the work of Lough et al (2005) on Atlantic cod. A third approach is incorporating environmental effects into multi-species Virtual Population Analysis. This approach was used by Jurado-Molina and Livingston (2002). They examined the influence of climate on trophicly linked groundfish species in the Bering Sea and found that the effects of climate change on recruitment had a comparable effect on population dynamics as fishing and predatory interactions (see also Livingston, 2000). The important need is the coupling of ecological models with ocean-climate models with the specified goal of providing scientific advice and forecasts to managers.

Resource Needs

- Investment is needed to redevelop the seawater laboratory facilities necessary to conduct the required laboratory research identified above. Additionally, ship time and equipment will be required for process-oriented field work. Finally, staff will be needed to operate laboratories and conduct field work.
- Resources and staff are required for synthesis and modeling activities. Activities will need to be coordinated with ongoing monitoring and research activities and with ongoing assessment activities. Interactions with climate models also will need to be developed.

Climate Information Needs

The climate information needs are the same as described in Section I.

III. Effects of Climate Change on Ecosystem Productivity

Description

Changes in ecosystem function or structure can impact fisheries separately from direct environmental effects and changes in species interactions. Large-scale regime shifts are well documented on the west coast (Hare and Mantua, 2000; Hollowed et al., 2001) and their influence on fisheries is being considered in the scientific advice process (Livingston, 2000; Jurado-Molina and Livingston, 2002). Such large-scale ecosystem changes have only recently been recognized on the east coast of North America. Frank et al. (2005) proposed that overfishing of benthic groundfish on the Scotian Shelf caused a re-organization of the ecosystem, whereby the abundance of small pelagic fishes and benthic macroinvertebrates increased markedly. The stability of the new ecosystem state is unknown, as is the potential composition of other stable states.

Changes similar to those noted on the Scotian Shelf have been documented in Narragansett Bay (an estuary bordering the northeast U.S. shelf), but these changes were linked to warming not fishing (Oviatt, 2004). A decrease in benthic groundfish was accompanied by an increase in pelagic fish and benthic invertebrates. Large-scale changes have also been noted in the Gulf of Maine and Georges Bank, but have yet to be linked to changes in fisheries. Mountain (2004) documented multi-year fluctuations in salinity and Greene et al. (2003) and Kane (2007) linked these salinity fluctuations to broad changes in zooplankton community structure in the Gulf of Maine and on Georges Bank. Work is underway now to understand the effects of these lower trophic level changes on fishery species. These studies indicate that the flow of energy in a system can change in response to fishing and climate change. A major challenge is understanding the system dynamics well enough to establish the cause of such changes and anticipate the timing and composition of new system states.

There are basic gaps in our knowledge of the northeast U.S. shelf ecosystem that limit our ability to describe and understand the response of the system to climate change. For example, in a recent review, Purcell (2005) concluded that gelatinous zooplankton will likely increase in temperate boreal systems as a result of ocean warming. Attrill et al. (2006) documented an increase in the abundance of jellyfish in the North Sea, which was correlated to positive phases of the NAO and lowering of pH. They coupled these statistical correlations to a climate model and forecasted that jellyfish abundance in the North Sea would increase. Such an increase would dramatically change the flow of energy through the system, as well as impact the recruitment of some fish species (see Lynam et al., 2005). In the northeast U.S. shelf ecosystem, gelatinous zooplankton may be a major component in the movement of energy through the system (Link et al., 2006), but our knowledge is incomplete at best and the effect of increases in abundance cannot be adequately assessed. Gelatinous zooplankton are but one example of a basic lack of knowledge of ecosystem structure that limits predictive capabilities of the effect of climate change on fisheries through ecosystem dynamics.

Ocean acidification also could have dramatic effects on northeast U.S. resources, but the issue is under-studied. Decreases in ocean pH are forecast to occur in the coming decades (Orr et al., 2005). These decreases will be caused by the ocean’s uptake of anthropogenic carbon dioxide from the atmosphere. Increased ocean CO_2 could have severe consequences for calcifying organisms (Caldeira, 2007), particularly those that produce aragonite (Orr et al., 2005). Changes in ocean CO_2 can also affect the physiological functions of fishes, and changes in these functions may reduce growth rate and population size (Ishimatsu et al., 2005). These are emerging issues that may result in ecosystem-scale changes similar to the effects of changing temperature. However, our ability to anticipate, let alone forecast, the effects of ocean acidification are limited by a basic lack of research.

In addition to changes in structure, at some large-scale, the amount of fisheries production in a system is linked to the amount of primary production (Nixon, 1988; Iverson, 1990). Changes in the magnitude of primary production could result in changes in the amount of fisheries production. Richardson and Schoeman (2004) found that sea surface warming in the Northeast Atlantic is accompanied by increasing phytoplankton abundance in cooler regions and decreased abundance in warmer regions. In Chesapeake Bay, climatic forcing appears to be a major factor in the timing and magnitude of primary productivity (Miller and Harding, 2007). Decreases in chlorophyll on the northeast U.S. shelf have been noted (http://www.nefsc.noaa.gov/omes/OMES/spring2007/advisory.html), but the causes and consequences of these changes on energy entering or moving through the system have not been investigated. However, there is an interesting correlation; haddock recruitment is highly correlated to the magnitude of the fall bloom (Friedland et al., 2008). The mechanisms behind the correlation have yet to be investigated but there is some evidence to suggest that climate-driven changes in primary production could impact the region's fisheries. The challenge is not only understanding the relationship between environment and individual species and the interactions among several species, but understanding the function of the system as a whole and building the tools that can convert this scientific understanding to management advice.

Current Activities

The Energy Modeling and Analysis eXercise (EMAX, Link et al., 2006) was undertaken by the NEFSC to evaluate the response of the northeast U.S. shelf ecosystem to a number of human perturbations, including climate change. The primary goal of EMAX was to establish an ecological network model of the entire food web. The model was parameterized based on the extensive datasets collected by the NEFSC over the past four decades. The emphasis is to explore the particular role of small pelagic fishes in the ecosystem and preliminary results show that these species are clearly keystone species in the ecosystem. The model is now being used for comparing the response of sub-artic ecosystems to climate change. In the future, EMAX will contribute to the development of Ecosystem-Based Approaches to Fisheries by serving as a coherent catalog of information and data, identifying major trophic fluxes in the ecosystem, serving as a basis for further analytical models, and acting as a tool for evaluating ecosystem responses to various system perturbations.

The NEFSC is also reviewing its Ecosystem Monitoring programs with the goal of collecting data to support single-species fishery management while also monitoring the biomass and production of the different components of the ecosystem. Future programs would build on current efforts, but take advantage of new technologies (e.g., video-plankton recorders, wet chemistry nutrient sensors) and new platforms (e.g., the NOAA Ship Henry Bigelow, autonomous underwater vehicles) to more thoroughly describe the ecosystem and monitor its components over time. The information gathered by future programs would support Ecosystem-Based Approaches to Management and would contribute to developing a quantitative understanding of the effect of climate change on fishery resources. The data could also be used to develop and evaluate the coupled ocean-climate models that will be used in forecasting the effects of climate change.

Research Needs

- Development of a suite of ecosystem models including network models, Nutrient-Phytoplankton-Zooplankon models (NPZ) models, habitat models, size-spectrum models, aggregated models that include the effect of the environment.
- Directed research to understand the effect of ocean acidification on resource species, their prey and predators, and overall ecosystem structure and function.
- Testing and evaluation of model assumptions and development of mechanistic understanding linking the environment to ecosystem dynamics
- Additional data collection to better understand ecosystem structure and function including environmental (e.g., pH, dissolved oxygen, nutrients), biomass, and production data for understudied species and functional groups (e.g., gelatinous zooplankton, benthic epifauna and infauna) and ecosystem-level data (e.g., biodiversity, size-spectra)

Modeling, monitoring, and research efforts are needed to develop the capacity for assessing the impact of climate on ecosystem structure and function to support the development of assessments. The EMAX project has developed a network, biomass-based, ecosystem model. This model needs to be linked with other regional ecosystem models to begin to understand the large-scale functioning of the ecosystem. For example, the northeast U.S. shelf model could be linked with estuarine specific models to better understand the importance of connections between the shelf and estuarine dynamics (Monaco and Ulanowicz, 1997). Similarly, the shelf model could be linked with models both upstream and downstream on the shelf (Bundy, 2005) to address the linkages across ecosystem boundaries and the effect that climate may have on these linkages.

Another approach that could contribute to understanding ecosystem effects on fisheries is Nutrient-Phytoplankton-Zooplankton (NPZ) modeling. These models provide a tool to examine the movement of energy and nutrients through the lower trophic levels. These NPZ models can be linked to individual species models to understand and forecast the effect of changes in the ecosystem on specific fishery species (Aydin et al., 2005; Werner et al., 2007).

Other modeling approaches need to be investigated including size-spectrum approaches, aggregated functional group approaches, and larger-scale ecosystem approaches. The overall goal of this work would be developing and evaluating models for their use in forecasting the effect of climate change of ecosystem productivity and in this regard the models need to include the mechanistic description of the effect of environmental change. These mechanisms can then be directly linked to climate forecasts. These models and mechanisms can also be evaluated through direct process-oriented research or comparative studies that utilize previously collected data.

In addition to modeling needs, ecosystem research and monitoring activities need to be augmented. There are components of the ecosystem that are not currently monitored, which may be very important to the flow of energy through the system (e.g., gelatinous zooplankton). Also, our measurement of surface properties is frequent and at fine resolution – satellites sample at spatial resolutions of kilometers and temporal resolutions of hours-days – but our measurements of subsurface properties is at the scale of 10 km’s and months. New technologies and collaborations will be needed to provide data for the ocean’s interior where much of the production and flow of energy occurs. Also, as mentioned above the effects of ocean acidification on resource species is an emerging issue. There is evidence of dramatic effects on resource species, but published studies are scarce. A large-scale effort is needed to determine the effects of ocean acidification on marine systems.

Finally, the role of Marine Protected Areas (MPAs) in protecting ecosystem structure and function in the face of climate change needs to be evaluated. Several studies have pointed out that the objectives of spatially fixed management approaches may be eroded by climate change (e.g., Burns et al. 2003). An MPA may protect spawning individuals today, but as spawning activities shift in response to changing climate, they may move outside of the protected area. This recognition requires an assessment of the vulnerability of MPAs to climate change. The goals and objectives of the protected area need to be quantified and then evaluated in terms of the effect of climate change on these goals and objectives. The individual, multi-species and ecosystem understanding described above will be critical to the ability to make these assessments.

Resource Needs

- Dedicated staff and resource to integrate satellite data and more comprehensive vertically discrete data into ecosystem models and fisheries assessments
- Dedicated staff and resources to develop and apply new technologies to the monitoring of marine ecosystems with an emphasis on those components of the ecosystem that are linked to environmental and climate change.
- Dedicated staff and resources to examine the direct and indirect effects of ocean acidification on resource species.
- Dedicated staff and resources to develop, test, and apply ecosystem models that include the effect of the environment on ecosystem structure and function

Climate Information Needs

- Regional coupled ocean-climate models that include ecosystem dynamics and are linked to basin-scale forcing
- Increased spatial and temporal measurements of the vertical structure of ocean properties (e.g., temperature, salinity, nutrients, plankton, components of the carbon cycle)
- Increased integration of ocean-climate data both from historical and ongoing data collection platforms

Regional coupled ocean-climate models need to be linked to the models of ecosystem structure and function. There are several ways to link ecosystem models (e.g., EcoPath and EcoSim) to climate models, but these methods have not been thoroughly evaluated. NPZ models have been linked to climate models (e.g., Pierce, 2004) and to the dynamics of higher trophic levels (Megrey et al., 2007; Rose et al., 2007). Size-spectrum and aggregate models could also be linked, but these modeling approaches and techniques need dedicated investigation. Such efforts need to be undertaken on the northeast U.S. shelf and need to occur in collaboration with the development of coupled ocean-climate models. One approach is to simply use outputs of climate models to force ecosystem models. However, a more productive approach would be the development of truly coupled ocean-climate-ecosystem models. The effect of climate on ecosystem would be included, but the effects of ecosystem on climate would also be included; such feedbacks may be an important component to forecasting climate change.

There is also need to include more information about the ocean interior in coupled ocean-climate models. The timing and magnitude of both the spring and fall bloom has been variable (see http://www.nefsc.noaa.gov/omes/OMES/spring2006/advisory.html), and there is evidence that the change in regional hydrographic properties and water column stratification plays a role. Stratification, which is common throughout the northeast U.S. shelf, is important to ecosystem dynamics and needs to be represented in coupled ocean-climate models. These processes can only be examined with observations made through the water column and with fully 3-D models that include the local, regional-scale and basin scales.

References

Able, K. W., and M. P. Fahay. 1998. First Year in the Life of Estuarine Fishes in the Middle Atlantic Bight. Rutgers University Press, New Brunswick, New Jersey

Anderson, J. T. 1988. A review of size dependent survival during pre-recruit stages of fishes in relation to recruitment. *Journal of Northwest Atlantic Fishery Science* 8: 55-66.

Attrill, M.J., J. Wright, and M. Edwards. 2007. Climate-related increases in jellyfish frequency suggest a more gelatinous future for the North Sea. *Limnology and Oceanography* 52: 480-485.

Aydin, K. Y., G. A. McFarlane, J. R. King, B. A. Megrey, and K. W. Myers. 2005. Linking oceanic food webs to coastal production and growth rates of Pacific salmon (*Oncorhynchus* spp.), using models on three scales. *Deep-Sea Research* 52: 757-780

Bourne, D. W., and C. S. Yentsch. 1987. Phytoplankton, primary production, and microbiology. in: Georges Bank Backus RH (ed.) pp. 210-212, MIT Press, Cambridge, MA.

Buckel, J. A., N. D. Steinberg, and D. O. Conover. 1995. Effects of temperature, salinity, and fish size on growth and consumption of juvenile bluefish. *Journal of Fish Biology* 47: 696-706

Buckley, L. J., and E. G. Durbin. 2006. Seasonal and inter-annual trends in the zooplankton prey and growth rate of Atlantic cod (*Gadus morhua*) and haddock (*Melanogrammus aeglefinus*) larvae on Georges Bank. *Deep Sea Research Part II: Topical Studies in Oceanography* 53: 2758-2770.

Bundy, A. 2005. Structure and functioning of the eastern Scotian Shelf ecosystem before and after the collapse of groundfish stocks in the early 1990s. *Canadian Journal of Fisheries and Aquatic Sciences* 62: 1453-1473

Burns, C. E., K. M. Johnston, and O. J. Schmitz. 2003. Global climate change and mammalian species diversity in U.S. national parks. *Proceedings of the National Academy of Sciences* 100: 11474-11477

Caldeira, K. 2007. What corals are dying to tell us about CO2 and ocean acidification. *Oceanography* 20: 188-195.

Ciannelli, L., G. E. Dingsør, B. Bogstad, G. Ottersen, K. S. Chan, H. Gjøsaeter, J. E. Stiansen, and N. C. Stenseth. 2007. Spatial anatomy of species survival: effects of predation and climate-driven environmental variability. *Ecology* 88: 635-646.

Claireaux, G., D. M. Webber, S. R. Kerr, and R. G. Boutilier. 1995. Physiology and behavior if free-swimming Atlantic cod (Gadus morhua) facing fluctuating salinity and oxygenetic conditions. *The Journal of Experimental Biology* 198: 61-69.

Clark, R. A, C. J. Fox, D. Viner, and M. Livermore. 2003. North Sea cod and climate change – modeling the effects of temperature on population dynamics. *Global Change Biology* 9: 1669-1680.

Collie, J. S., and P. D. Spencer. 1994. Modeling predator-prey dynamics in a fluctuating environment. *Canadian Journal of Fisheries and Aquatic Sciences* 51: 2665-2672.

Cohen, A. L., D. C. McCorkle, and S. de Putron. 2007. The impact of seawater saturation state on early skeletal development in larval corals: insights into scleractinian biomineralization. *Eos Trans. AGU* 88(52), Fall Meet. Suppl., Abstract: B31D-0618.

Cooper, R. A., P. Valentine, J. R. Uzmann, and R. A. Slater. 1987. Submarine canyons. p. 52-63. In Georges Bank, Backus RH (eds.) MIT Press, Cambridge, Massachusetts.

Cox, J., and P. H. Wiebe. 1979. Origins of oceanic plankton in the Middle Atlantic Blight. *Estuarine and Coastal Marine Science* 9: 509-527.

Cushing, D. H. 1990. Plankton production and year-class strength in fish populations: an update of the match/mismatch hypothesis. *Advances in Marine Biology* 26: 249–293.

Enfield, D. B., A. M. Mestas-Nunez, and P. J. Trimble. 2001: The Atlantic Multidecadal Oscillation and its relationship to rainfall and river flows in the continental U.S. *Geophysical Research Letters* 28: 2077-2080.

Fahay, M. P., P. L. Berrien, D. L. Johnson, and W. M. Morse. 2004. Atlantic cod, *Gadus morhua,* life history and habitat characteristics. NOAA Tech Memo NE-190.

Fahay, M. P. 2007. Early stages of fishes in the western North Atlantic Ocean (Davis Strait, Southern Greenland and Flemish Cap to Cape Hatteras. North Atlantic Fisheries Organization, Dartmouth, Nova Scotia.

Feely, R. A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, F. J. Millero. 2004. Impact of anthropogenic CO_2 on the $CaCO_3$ system in the oceans. *Science* 305: 362-366.

Fogarty, M. J., L. Incze, K. Hayhoe, D. Mountain, and J. Manning. 2008. Potential climate change impacts on Atlantic cod (*Gadus morhua*) off the northeastern USA. *Mitigation and Adaptive Strategies for Global Change* 13: 453-466.

Frank, K. T., B. Petrie, J. S. Choi, and W. C. Leggett. 2005. Trophic cascades in a formerly cod-dominated ecosystem. *Science* 308: 1621-1623.

Friedland, K. D., J. A. Hare, G. B. Wood, L. A. Col, L. J. Buckley, D. G. Mountain, J. Kane, J. Brodziak, R. G. Lough, and C. H. Pilskaln. 2008. Does the fall phytoplankton bloom control recruitment of Georges Bank haddock, *Melanogrammus aeglefinus,* through parental condition? *Canadian Journal of Fisheries and Aquatic Sciences* 65: 1076-1086.

Friedland, K. D., and J. A. Hare. 2007. Long term trends and regime shifts in sea surface temperature on the continental shelf of the northeastern United States. *Continental Shelf Research* 27: 2313-2328.

Friedland, K. D., M. J. Miller, and B. Knights. 2007. Oceanic changes in the Sargasso Sea and declines in recruitment of the European eel. *ICES Journal of Marine Science* 64: 519-530.

Friedland, K. D., D. G. Reddin, and M. Castonguay. 2003. Ocean thermal conditions in the post-smolt nursery of North American Atlantic salmon. *ICES Journal of Marine Science* 60: 343-355.

Friedland, K. D., D. G. Reddin, J. R. McMenemy, and K. F. Drinkwater. 2003. Multi-decadal trends in North American Atlantic salmon stocks and climate trends relevant to juvenile survival. *Canadian Journal of Fisheries and Aquatic Science* 60:563-583.

Frumhoff, P. C., J. J. McCarthy, J. M. Melillio, S. C. Moser, and D. J. Wuebbles. 2007. Confronting climate change in the U.S. Northeast: Science, impacts, and solutions. Synthesis report of the Northeast Climate Impact Assessment, Cambridge, Massachusetts. Union of Concerned Scientists

Greene, C. H., A. J. Pershing, R. C. Kenney, and J. W. Jossi. 2003. Impact of climate variability on the recovery of North Atlantic right whales. *Oceanography* 16:98-103

Grimes, C. B., K. W. Able, and R. S. Jones. 1986. Tilefish, *Lopholatilus chamaeleonticeps,* habitat, behavior and community structure in Mid-Atlantic and southern New England waters. *Environmental Biology of Fishes* 15: 273-292.

Hare, J. A., and K. W. Able. 2007. Mechanistic links between climate and fisheries along the east coast of the United States: explaining population outbursts of Atlantic croaker (*Micropogonias undulatus*). *Fisheries Oceanography* 16: 31-45.

Hare, S. R., and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989. *Progress in Oceanography* 47: 103-146.

Hollowed, A. B., S. R. Hare, and W. S. Wooster. 2001. Pacific-basin climate variability and patterns of Northeast Pacific marine fish production. *Progress in Oceanography* 49:257-282.

Hunt, J. J., W. T. Stobo, and F. Almeida. 1998. Movement of Atlantic cod, *Gadus morhua*, tagged in the Gulf of Maine area. *Fishery Bulletin* 97: 842-860.

Hurrell, J. W., Y. Kushnir, M. Visbeck, and G. Ottersen (eds) 2003. An overview of the North Atlantic Oscillation. Geophysical Monograph Series, American Geophysical Union, Washington D.C.

Hurst, T. P., and D. O. Conover. 1998. Winter mortality of young-of-the-year Hudson River striped bass (*Morone saxatilis*): size-dependent patterns and effects on recruitment. *Canadian Journal of Fisheries and Aquatic Sciences* 55: 112-1130.

Hurst, T. P. 2007. Causes and consequences of winter mortality in fishes. *Journal of Fish Biology* 71: 315–345.

Hutchinson, R. E. 1965. The ecological theater and the evolutionary play. Yale University Press, New Haven Connecticut 139 p.

Ishimatsu, A., M. Hayashi, K.-S. Lee, T. Kikkawa, and J. Kita. 2005. Physiological effects on fishes in a high-CO_2 world, *Journal Geophysical Research* 110, C09S09, doi:10.1029/2004JC002564.

Iverson, R. L. 1990. Control on marine fish production. *Limnology and Oceanography* 35: 1593-1604

Juanes, F., and D. O. Conover. 1995. Size-structure piscivory: advection and the linkage between predator and prey recruitment in young-of-the year bluefish. *Marine Ecology Progress Series* 128: 287-304.

Jurado-Molina, J., and P. Livingston. 2002. Climate-forcing effects on trophically linked groundfish populations: implications for fisheries management. *Canadian Journal of Fisheries and Aquatic Sciences* 59: 1941-1951.

Kane, J. 2007. Zooplankton abundance trends on Georges Bank, 1977–2004. *ICES Journal of Marine Science* 64: 909–919.

Kerr, R. A. 2000. A North Atlantic climate pacemaker for the centuries. *Science* 288: 1984-1986.

Kerr, R. A. 2005. Atlantic climate pacemaker for millennia past, decades hence? *Science* 309: 43-44.

Kohler, N. E., J. G. Casey, and P. A. Turner. 1998. NMFS Cooperative Shark Tagging Program, 1962-1993: An atlas of shark tag and recapture data. *Marine Fisheries Review* 60: 1-87.

Lehodey, P., J. Alheit, M. Barange, T. Baumgartner, G. Beaugrand, K. Drinkwater, J.-M. Fromentin, S. Hare, G. Ottersen, R. I. Perry, C. Roy, C. D. van der Lingen, and F. Werner. 2006. Climate variability, fish and fisheries. *Journal of Climate* 19: 5009–5030.

Link, J. S., C. A. Griswold, E. T. Methratta, and J. Gunnard, Editors. 2006. Documentation for the Energy Modeling and Analysis eXercise (EMAX). US Dep. Commer., Northeast Fish. Sci. Cent. Ref. Doc. 06-15; 166 p

Livingston, P. A. 2000. A multispecies virtual population analysis of the eastern Bering Sea. *ICES Journal of Marine Science* 57:294-299.

Lough, R. G., L. J. Buckley, F. E. Werner, J. A. Quinlan, K. Pehrson Edwards. 2005. A general biophysical model of larval cod (*Gadus morhua*) growth applied to populations on Georges Bank. *Fisheries Oceanography* 14: 241-262.

Lynam, C. P., M. R. Heath, S. J. Hay, and A. S. Brierley. 2005. Evidence for impacts by jellyfish on North Sea herring recruitment. *Marine Ecology Progress Series* 298: 157-167

MacKenzie, B. R., and F. Köster. 2004. Fish production and climate: sprat in the Baltic Sea. *Ecology* 85: 784–794.

Manderson, J. P., J. Pessutti, P. Shaheen, and F. Juanes. 2007. Dynamics of early juvenile winter flounder predation risk on a North West Atlantic estuarine nursery ground. *Marine Ecology Progress Series* 328: 249-265.

Megrey, B. A., K. A. Rose, S. Ito, D. E. Hay, F. E. Werner, Y. Yamanaka, and M. N. Aita. 2007. North Pacific basin-scale differences in lower and higher trophic level marine ecosystem responses to climate impacts using a nutrient-phytoplankton–zooplankton model coupled to a fish bioenergetics model. *Ecological Modeling* 202: 196-210

Miller, W. D., and L. W. Harding. 2007. Climate forcing of the spring bloom in Chesapeake Bay. *Marine Ecology Progress Series* 331: 11-22.

Monaco, M. E., and R. E. Ulanowicz. 1997. Comparative ecosystem trophic structure of three US mid-Atlantic estuaries. *Marine Ecology Progress Series* 161: 239-254

Mountain, D. G. 2000. Potential consequences of climate change for the fish resources in the Mid-Atlantic Bight. In: Fisheries in a changing climate, American Fisheries Society Symposium 32. N.A. McGinn (ed.), American Fisheries Society, Bethesda, Maryland, pp. 185-194.

Mountain, D. G. 2003. Variability in the properties of shelf water in the Middle Atlantic Bight, 1977–99. *Journal of Geophysical Research* 108(C1), 3014, doi:10.1029/2001JC001044.

Mountain, D. G. 2004. Variability of the water properties in NAFO subareas 5 and 6 during the 1990s. *Journal of Northwest Atlantic Fishery Science* 34: 103-112 doi:10.2960/J.v34.m475

Mountain, D. G., and T. J. Holzwarth. 1989. Surface and bottom temperature distribution for the northeast continental shelf. NOAA Tech. Mem. NMFS-F/NEC-73; 32 p.

Murawski, S. A. 1993. Climate change and marine fish distributions: Forecasting from historical analogy. *Transactions of American Fisheries Society* 122: 647–658.

Myers, R. A. 1998. When do environment-recruit correlations work? *Reviews in Fish Biology and Fisheries* 8: 285-305.

Nixon, S. W. 1988. Physical energy inputs and the comparative ecology of lake and marine ecosystems. *Limnology and Oceanography* 33: 1005-1025.

Ohman, M. D., K. Eianeb, E. G. Durbinc, J. A. Runge, and H.-J. Hirche. 2004. A comparative study of *Calanus finmarchicus* mortality patterns at five localities in the North Atlantic. *ICES Journal of Marine Science* 61: 687-697.

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.

Oviatt, C. A. 2004. The changing ecology of temperate coastal waters during a warming trend. *Estuaries* 27: 895-904.

Peck, M. A., L. J. Buckley, E. M. Caldarone, and D. A. Bengtson. 2003. Effects of food consumption and temperature on growth rate and biochemical-based indicators of growth in early juvenile Atlantic cod *Gadus morhua* and haddock *Melanogrammus aeglefinus*. *Marine Ecology Progress Series* 251: 233-243.

Petersen, J. H., and J. F. Kitchell. 2001. Climate regimes and water temperature changes in the Columbia River: bioenergetic implications for predators of juvenile salmon. *Canadian Journal of Fisheries and Aquatic Sciences* 58: 1831-1841.

Pierce, D. W. 2004. Future changes in biological activity in the North Pacific due to anthropogenic forcing of the physical environment. *Climatic Change* 62: 389-418.

Pineda, J., J. A. Hare, and S. Sponaugle. 2007. Larval transport and dispersal in the coastal ocean and consequences for population connectivity. *Oceanography* 20: 24-41.

Platt, T., C. Fuentes-Yaco, and K. T. Frank. 2003. Spring algal bloom and larval fish survival. *Nature* 423: 398-399

Purcell, J. E. 2005. Climate effects on formation of jellyfish and ctenophore blooms: a review. *Journal of the Marine Biological Association of the UK* 85: 461-476

Richardson, A. J., and D. S. Schoeman. 2004. Climate impact on plankton ecosystems in the Northeast Atalntic. *Science* 305: 1609-1612.

Rose, K. A., F. E. Werner, B. A. Megrey, M. N. Aita, Y. Yamanaka, D. E. Hay, J. F. Schweigert, and M. B. Foster. 2007. Simulated herring growth responses in the Northeastern Pacific to historic temperature and zooplankton conditions generated by the 3-dimensional NEMURO nutrient–phytoplankton–zooplankton model. *Ecological Modeling* 202: 184-195.

Stevenson, D., L. Chiarella, D. Stephan, R. Reid, K. Wilhelm, J. McCarthy, and M. Pentony. 2003. Characterization of the fishing practices and marine benthic ecosystems of the northeast U.S. shelf, and an evaluation of the potential effects of fishing on essential fish habitat. NOAA Technical Memorandum NMFS-NE-181.

Sullivan, M. C., K. W. Able, J. A. Hare, and H. J. Walsh. 2006. Anguilla rostrata glass eel ingress into two U.S. east coast estuaries: patterns, processes and implications for adult abundance. *Journal of Fish Biology* 69: 1081-1101.

Theroux, R. B., and R. L. Wigley. 1998. Quantitative composition and distribution of the macrobenthic invertebrate fauna of the continental shelf ecosystems of the northeastern United States. NOAA Technical Report NMFS 140.

Trippel, E. A., and S. R. E. Neil. 2004. Maternal and seasonal differences in egg sizes and spawning activity of northwest Atlantic haddock (*Melanogrammus aeglefinus*) in relation to body size and condition. *Canadian Journal of Fisheries and Aquatic Sciences* 61: 2097-2110.

Waring, G. T., T. Hamazaki, D. Sheehan, G. Wood, and S. Baker. 2001. Characterization of beaked whale (Ziphiidae) and sperm whale (*Physeter macrocephalus*) summer habitat in shelf edge and deeper waters off the northeast U.S. Marine Mammal Science 17: 703–717.

Weinberg, J.R. 2005. Bathymetric shift in the distribution of Atlantic surfclams: response to warmer ocean temperature. *ICES Journal of Marine Science* 62: 1444-1453.

Werner, F. E., S. I. Ito, B. A. Megrey, and M. J. Kishi. 2007. Synthesis of the NEMURO model studies and future directions of marine ecosystem modeling. *Ecological Modeling* 202: 211-223.

Williams, A. B. 1984. Shrimps, lobsters, and crabs of the Atlantic coast of the eastern United States, Maine to Florida. Smithsonian Institution Press, Washington D.C.

Wu, A., W. W. Hsieh, and A. Shabbar. 2005: The nonlinear patterns of North American winter temperature and precipitation associated with ENSO. *Journal of Climate* 18: 1736-1752.

Southeast U.S. Continental Shelf, Gulf of Mexico, and U.S. Caribbean

Author:
Michael Burton
(Southeast Fisheries Science Center)

Introduction

The southeastern United States region includes the continental shelf ecosystem extending from Cape Hatteras, North Carolina through to the Texas-Mexico border, as well as the insular areas of Puerto Rico and the U. S. Virgin Islands. There are substantial biological, climatic, and geological differences between the temperate and tropical areas of the overall managed region. These areas are influenced by the warm waters of the Florida Current and its northward extension, the Gulf Stream (Fig 1.). The temperate area, represented by wide-shelf systems, includes the area from Cape Hatteras to Cape Canaveral, Florida and the Gulf of Mexico. This area supports important commercial and recreational fisheries, as well as valuable recreational tourist industries such as charter fishing, SCUBA diving, and recreational boating. The tropical component of the region is represented by the narrow shelf systems of the area from Jupiter, FL to the Dry Tortugas, FL, as well as Puerto Rico and the U. S. Virgin Islands. These areas are best known for the presence of coral reefs and the diverse tropical fish communities that accompany them. The island regions support important subsistence fisheries as well as tourist industries, both dependent on healthy coral reef ecosystems.

Fig.1. Southeast U.S., Gulf of Mexico and U.S. Caribbean.

Climate Induced Ecosystem Concerns

The major climate induced ecosystem concerns for the southeast U.S. continental shelf, Gulf of Mexico and U.S. Caribbean in order of importance are:

I. Threats to coral reef ecosystems: coral bleaching, disease, and ocean acidification
II. Threats to habitat from sea level rise – loss of essential fish habitat
III. Climate induced changes to species phenology and distribution

I. Threats to coral reef ecosystems: coral bleaching, disease, and ocean acidification

Description

Coral reef ecosystems are increasingly recognized in the scientific and management communities as among the most threatened ecosystems on Earth. Tropical hard corals are the foundation of these ecosystems, building the physical structure which provides fisheries habitat, coastal protection, and recreational value. Mass coral bleaching episodes in the Southeast (Florida and Caribbean) have been increasing in frequency over the past decades, thought to be primarily in response to an increase in high temperature events (Marshall and Schuttenberg, 2006).

Another mechanism of climate impact on corals is disease virulence and the potential for coincidence with temperature induced bleaching events (Jones et al., 2004). Recent laboratory experiments show that corals affected by yellow band disease suffer significantly greater rates of mortality at increased temperature (i.e., 32°C) than either unaffected corals at 32°C or affected corals at moderate temperature (Cervino et al., 2004). Warm temperatures correlate with increased incidence of White Pox disease on *A. palmata* (Patterson et al., 2002).

Fig. 2. Diseased Elkhorn coral, *Acropora palmata*. Photo courtesy of Margaret Miller, NMFS, SEFSC, Miami, FL.

Thus, coral colonies subject to heat stress may additionally be more susceptible to disease. Recent observations following the massive 2005 Caribbean bleaching event support this possibility. Many bleached colonies in the U.S. Virgin Islands were observed to recover from bleaching, but subsequently succumb to disease mortality (Muller et al.,2008; Miller et al., 2006).

Both shallow and deep water corals are also susceptible to ocean acidification as declining pH/carbonate saturation state of seawater reduces the calcification rate of reef-building corals. That is, building of coral skeleton and hence, reef habitat for fisheries, becomes more energetically expensive and occurs at a reduced rate. This phenomenon, along with bleaching and disease, increases the risk to already fragile coral ecosystems.

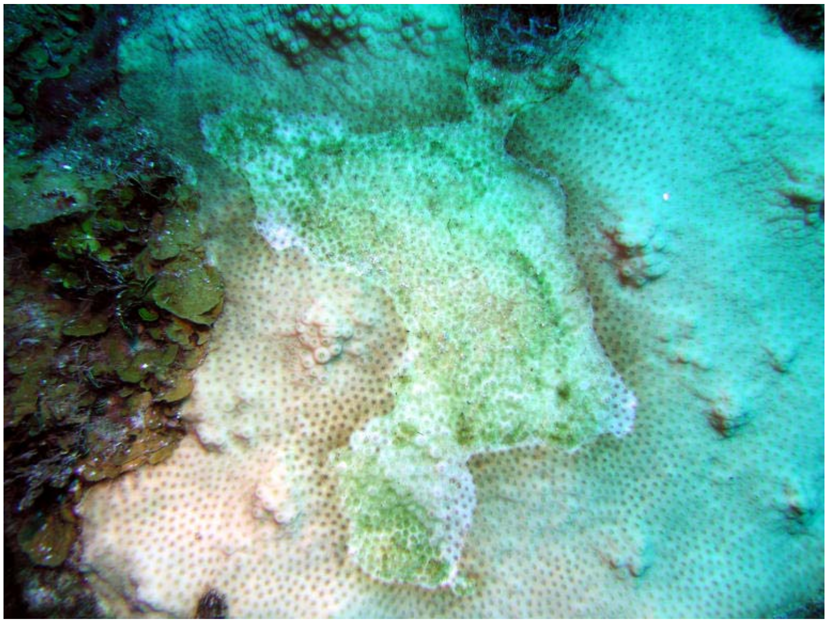

Fig. 3 Mountainous star coral, *Montastrea faveola*, showing bleaching and disease. Photo courtesy of Margaret Miller, NMFS, SEFSC, Miami, FL.

Current Activities

Currently monitoring of coral bleaching events and water quality is being conducted throughout the southeastern U.S. and Caribbean in areas where coral bleaching is an issue. The NOAA Coral Reef Conservation Program is working to raise awareness of coral bleaching events and to identify outbreaks of coral disease. Satellites are used to derive an index of cumulative high ocean temperatures, called Degree-Heating Weeks, in order to predict where severe bleaching events may occur. There is a cooperative bleaching assessment effort in Florida conducted under the auspices of the Florida Reef Resilience Program.

Some laboratory experiments are ongoing in various academic laboratories to determine the causes and mechanisms of coral bleaching and disease, as well as the impacts of ocean acidification on hard corals. Some current research activities are seeking predictive patterns between broad scale temperature patterns (e.g. satellite sea surface temperature) and observed disease outbreaks.

Research Needs

1. Targeted and rapid effort to elucidate the mechanisms and develop strategies to ameliorate the synergies of warming, coral bleaching, and coral health/disease.

There are currently no effective management or mitigation actions to curtail coral mortality from bleaching and disease, which will continue to get worse in the near and medium-term future. This represents a huge obstacle in effective recovery planning for Endangered Species Act listed corals, *Acropora palmata* and *A. cervicornis*. Accelerated research activities to determine the causes of coral diseases, the ecology of coral microbial pathogens, and the effects of increased temperature or acidity on mechanisms of coral resistance/immunity to disease are crucial for identifying possible mitigating actions to curtail the accelerating pace of coral loss in Florida and the Caribbean.

2. Understand the likely effects of increased acidification on larval recruitment of corals.

Larval corals of broadcast spawning species lack symbiotic algae and so spend one to several weeks swimming in the plankton without the benefit of feeding or photosynthetic subsidy. Hence energy may become a limiting factor for these larvae in completing settlement and metamorphosis (onset of calcification) when in a more acidic environment.

3. Continue documenting species composition, diversity, and abundance of reef fish communities under regimes of declining coral habitat and conduct studies to understand fish species' dependence on coral habitat to anticipate changes in species composition.

As corals die from bleaching or disease, architectural habitat complexity may be maintained by standing dead coral skeletons in the short term. However, increasing erosive processes under altered climate regimes (e.g., acidification and/or increased hurricane intensity/frequency) may accelerate degradation of reef fish habitat.

Resource Needs

The resource needs to address coral mortality from bleaching and diseases are acute. A wide range of resources (e.g., funding for external grants, laboratory infrastructure for microbial challenge experiments, live coral material for laboratory experiments) are needed to accelerate research in this area to develop mitigation strategies to abate currently observed rates of coral mortality. Such activities could be coordinated via the Coral Disease and Health Consortium.

Climate Information Needs

Predictive capacity for coral bleaching events is fairly well-developed. Climate information needs are much greater with regards to acidification/alkalinity. These needs include:

1. Seawater pH in reef waters.
2. Temporal (e.g., seasonal, decadal) and spatial (e.g., geographic, with depth) variation in reef pH.
3. Determining predictive relationships or proxies among other environmental factors which are easier to measure (e.g. remotely sensed).

II. Threats to habitat from sea level rise – loss of essential fish habitat

Description

Coastal wetlands in the northern Gulf of Mexico provide critically important fishery habitat, supporting large fisheries on shrimp, blue crabs, red drum, southern flounder, spotted sea trout, and menhaden. These wetlands are threatened by rising sea level because their existence depends upon a balanced tolerance to tidal inundation that will be exceeded under most sea level rise scenarios. Increased inundation from sea level rise causes loss of wetlands. Salt water intrusion kills salt-intolerant vegetation, making barrier islands and wetlands more vulnerable to increased wave action and erosion from coastal storms and hurricanes, leading to loss of land.

The different bay systems in the Gulf of Mexico vary in their fishery production potential. The link between habitat and associated fishery production in these systems, however, is not understood well enough to explain this variation, either under current conditions or in the face sea level rise under different climate change scenarios. Investment in this area of ecosystem science is needed to support future management of the Gulf of Mexico fisheries.

Sea level rise could also lead to loss/changes in estuarine habitat and coastal habitat used by bottlenose dolphins and their prey. This habitat loss might adversely affect the dolphin populations in some or all of the following ways:

- Change in prey abundance and/or availability
- Change in "nursery" areas for mothers with calves
- Disruption of social structure, breeding structure
- Disruption of migratory patterns

Current Activities

A multi-agency effort is underway to measure sea level rise and assess the rate of land (marsh) subsidence in impacted areas such as Louisiana. Since most of the geodetic and water level data needed to do this accurately are more than two decades old, NOAA is cooperating with local and state agencies in a two-stage approach to acquire the necessary information to effectively monitor threats from sea level rise.

NOAA Fisheries is conducting inundation analyses to assess the effects of frequency and duration of inundation on marsh vegetation by high waters at water level stations. NOAA Fisheries Restoration Center is also actively engaged in on-the-ground restoration projects in Louisiana.

The abundance and distribution of resident estuarine, coastal migratory, and pelagic stocks of bottlenose dolphins are monitored along the southeastern U.S. coast using a combination of small-boat based and aerial visual surveys. The surveys range in frequency from monthly/seasonal to irregular. While none of the abundance estimates are precise enough to detect small changes in population trends, they are capable of detecting large changes in population size. The detection of fine scale changes in population size will require a more detailed monitoring program. The current sampling regime is designed to collect baseline population estimates of bottlenose dolphin stocks that can be compared to future estimates in order to assess the health of marine mammal stocks. These population assessments will provide valuable information to scientists studying the effects of climate variability on living marine resources of the southeastern United States.

Research Needs

1. Model effects of changing sea level regimes on fishery production and yields. This research would characterize wetland support systems in different estuaries of the northern Gulf of Mexico in relation to their potential for fishery production. Specific objectives should include:

    a. Sample habitat specific densities and measure growth rates of juvenile fishery species in a range of estuarine systems of the Gulf using comparable quantitative methods.

    b. Characterize and predict changes in wetlands by combining analyses of land-water patterns derived from remote imagery with field measurements of marsh slope and elevation.

This part of the study will rely heavily on the extensive series of tide gauges already established by the National Ocean Service to define current inundation regimes.

c. Complete development of production models for key fishery species (shrimp, blue crab, red drum, southern flounder and others) and parameterize the models for different estuarine systems in the Gulf.

2. Select marine mammal stocks with sufficiently large populations and relatively limited distribution patterns in areas predicted to experience impacts from climate change and establish fine scale monitoring programs aimed at understanding marine mammal ecology, reproduction and feeding behavior. Understanding the food habits of most marine mammals is difficult as most stomach samples come from sick or stranded animals. More in-depth studies on feeding ecology are needed and once major prey sources are identified these trophic interactions, including changes in prey distribution and abundance in response to climate change, need to be monitored.

3. Generate digital elevation models that can be used to assist with the design, construction and engineering of new marsh surfaces by linking tidal databases to geodetic databases using GPS and leveling techniques.

Resource Needs

We don't have a good handle on what the effect on fisheries production would be for different rates of sea level rise. Simulation models should be developed or improved that could predict how changes in sea level would affect coastal habitats and the fisheries that depend on them. Scale is an important consideration in these models (i.e., models that are relevant at the scale of an estuary would be more useful to the fisheries management community than those at the scale of the northern Gulf coast). NOAA should dedicate resources to understand the relationships among climate change, accelerated sea level rise, wetlands, and coastal fishery production. The goal should be to develop simulation models that could predict the change in coastal fisheries production from climatic conditions.

Monitoring of marine mammal stocks at the intensity necessary to detect small changes in population parameters is not possible given current funding and staffing levels. Currently, no site is monitored at the level required and monitoring that does occur is conducted irregularly. The monitoring would need to be increased by at least an order of magnitude to provide the data required to evaluate population parameters. Several estuarine and nearshore sites along the Atlantic coast and in the Gulf of Mexico would need to be selected and monitored. Monitoring would include satellite-linked telemetry studies to describe habitat usage, sampling to estimate abundance, and sampling to monitor changes in other population parameters (e.g., survival, disease processes). This would require significant expansion of the marine mammal staff as well as significant increases in travel and field operations budgets. Some of the necessary studies could be conducted in cooperation with academic programs, but this would not negate the need for more FTEs and increased operating budgets.

Climate Information Needs

1. Sea surface temperature over a broad spatial area – necessary to study linkages between climate change and distribution of living marine resources, especially pelagic species.
2. Bottom temperature data – an important factor for many fisheries species, limiting their distribution.
3. Long term monitoring of sea level rise at fixed stations located in important wetland areas.

III. Climate induced changes to species phenology and distribution

Description

Ocean warming caused by climate change, while not directly causative of marine species invasions, could allow establishment of non-indigenous species through changing thermal regimes more tolerable to the invasive species. Marine species invasions have the potential to lead to fundamental shifts in the ecology of a region by modifying ecosystem processes, community composition and food-web dynamics (Verlaque and Fritayre, 1994; Shiganova, 1998; Grosholz et al., 2000). Semmens et al. (2004) document 16 non-native species that have been seen in biological surveys in the southeastern United States since 1999. The suspected mechanism for release in U.S. waters is either ballast water or aquarium release. Lionfish (*Pterois volitans*) is the most recent species to gain notoriety as an invasive species, being found in the warm-temperate waters from northern Florida to North Carolina in water depths from 35 to 90 meters. While lionfish are currently limited to these thermally stable depths by minimum winter water temperatures, a warming climate has the potential to increase lionfish growth rates, increase the length of the reproductive season, shift the range of lionfish northward, and release them from the current depth limits by increased inshore winter bottom temperatures. This would allow them to settle in shallower habitats, increase the ecological impact on native community species, and would likely result in increased numbers of negative human interactions as more divers and fisherman encountered their venomous spines.

Two climate change impacts on fisheries are: a) shifts in spawning seasons (observable through either gonadosomatic indices of adult fish from fishery-dependent samples or spawning date back-calculations from juvenile fish in a fishery-independent survey); and b) changing migration dates / routes in coastal pelagics such as cobia and mackerel. These could be related to climate change either directly (i.e., increasing seawater temperatures result in longer spawning seasons) or indirectly (changing temperatures influence prey availability, disrupting migration patterns). In the case of expanded spawning seasons, those stocks of fish could be subjected to extra fishing pressure due to the targeting of spawning aggregations. The disruption and altering of migration routes, evolved over generations, could lead to reproduction failures and stock collapse. These changes are difficult to discern given the extent of annual variation and require long-term (20 years +) monitoring. A third possible impact is the effect of changing climate on basic life history parameters such as growth rates. Environmental variability can strongly affect fish growth, though the degree of this influence is still poorly quantified for many species. Such studies would require high quality, long-term time series of growth data.

Climate change also has the potential to affect sea turtles. All sea turtle species studied to date exhibit temperature-dependent sex determination, with higher incubation temperatures producing a greater number of female hatchlings (Mrosovsky, 1994). As a result, if sea turtles continue to only use existing nesting sites, increases in global temperatures will increase the proportion of females in sea turtle populations and an insufficient number of males in breeding populations may limit reproductive success. Within the aquatic environment, as sea turtles are predominantly poikilothermic organisms, their northern range is limited by water temperature, with individuals most often preferring temperatures of 14ºC or greater (Witzell and Azarovitz, 1996). Increases in overall water temperature may result in extended foraging seasons in northern areas, or an overall shift in foraging habitat, if tropical areas become unsuitable due to extremely high temperatures. This expansion or shift of sea turtle habitat northward along the coast has the potential to increase interactions with fishing gears that might account for a rise in anthropogenic mortality. Increased contact between animals originating from diverse areas in newly-available foraging habitats has the potential to facilitate transmission of diseases into previously unaffected areas. Although fibropapilloma (FP), a potentially lethal, tumor-causing disease, has typically only been found in turtle populations inhabiting tropical areas such as Florida and Hawaii, recently FP has been detected in two turtles from North Carolina waters, a previously unaffected area (Harms et al., 2004). Additionally, increased water temperatures can exacerbate the severity of symptoms in diseased turtles (George, 1997). On a broader scale, warming water temperatures and increased sea levels have the potential to appreciably modify extant oceanic current regimes, which would affect migratory pathways, foraging habitat availability, and feeding strategies for all sea turtle life stages, oceanic and neritic. The El Niño Southern Oscillation in the Pacific has been linked to the availability of prey and the frequency of leatherback (Saba et al., 2006) and green turtle (Limpus and Nicholls, 1988) nesting, suggesting that altered current regimes could significantly influence the reproductive success of sea turtles.

Climate change will inevitably affect ocean processes and hence marine life on all space and time scales. For example, global scale changes in ocean circulation will eventually affect regional and local marine populations due to the connectivity of the ocean current systems. A slowing down or speeding up of the Atlantic Subtropical Gyre will cause changes in the Loop Current and Gulf Stream that may dramatically affect larval distribution patterns in the Caribbean and Gulf of Mexico. Feedback mechanisms between large-scale meteorological phenomena, such as the North Atlantic Oscillation, and the inter-tropical convergence zone, sea surface temperatures and wind-driven currents may have important implications for the regional ecosystems and will need to be taken into account for successful, sustainable fishery management.

Fig. 4. Lionfish, *Pterois volitans*, feeding on purple reef fish on hardbottom habitat off North Carolina. Photo courtesy of Doug Kesling, NOAA, NURC, UNC-Wilmington.

Current Activities

NMFS and NOS research at the NOAA Beaufort Laboratory is assessing the ecological impacts of lionfish on marine ecosystems of the western Atlantic; developing a quantitative model of dispersal aimed at understanding the mechanisms influencing the spread of lionfish, assessing human interactions and impacts, and evaluating factors facilitating the introduction in the hopes of using this information to prevent, mitigate, and manage future introductions. Researchers have initiated the long term monitoring of bottom seawater temperatures and fish community composition at several offshore sites in order to better understand the link between climate change and changing biodiversity.

Currently the SEFSC conducts fishery dependent sampling programs in recreational and commercial fisheries from North Carolina throughout the entire Gulf of Mexico. Samplers collect hard parts for ageing and gonads for reproductive studies as requested. Most of this work concentrates on data needs of stock assessment scientists for updated age-growth studies. MARMAP conducts fishery independent sampling in the Atlantic Ocean from North Carolina waters to Florida, collecting mostly adult fishes using trap and hook and line gear. Otoliths and gonads are collected on all fishes. The archived otolith databases from these surveys could yield valuable information about the effect of climate change on growth rates of reef fishes as well as to changes in timing of annuli deposition that might occur due to changing water temperatures. Additionally, there is one long-term fishery independent survey collecting larval and juvenile fishes systematically at one location, the Beaufort Bridge-net Survey. Specimens collected from this survey could be processed for back-calculation of spawning dates to determine if climate change is affecting timing of reproduction in fishes.

SEFSC researchers have recently initiated a study examining the usefulness of dendrochronology (tree ring techniques) to better understand these interrelationships between recruitment, growth, and the effects of climate variability. Using archived red snapper (*Lutjanus campechanus*) otoliths, scientists are developing a high-resolution chronology using ring widths of otolith growth increments. Red snapper is sufficiently long-lived to construct a chronology several decades in length. As indicated by periods of episodic recruitment, including several years since 1989, red snapper may be sensitive to environmental variability. If climate is an important driver of the ecology and reproduction of this species, awareness of climate-growth relationships may help improve management of this valuable species.

In 1980 NMFS formally established the Sea Turtle Stranding and Salvage Network (STSSN) with the intent of documenting sea turtle strandings along the Atlantic and Gulf coasts of the U.S. The network mainly encompasses the coastal areas of eighteen states from Maine to Texas, and is carried out through cooperation with the U. S. Fish and Wildlife Service and the wildlife and fisheries agencies specific to each participatory state. Network participants collect detailed information regarding all reported strandings, including date, location, species, condition, whether any tags are present on the turtle, size, weight, and any distinguishing marks. When possible, necropsies are conducted to attempt to determine cause of death and the sex of the stranded animal. Stranding information is compiled within a centralized STSSN data base that is made available to the public (http://www.sefsc.noaa.gov/seaturtleSTSSN.jsp).

Beginning in 1988, NMFS established a long-term sea turtle research program to assess sea turtle populations in the inshore waters of North Carolina. NMFS biologists accompany pound net fishermen to their nets and any captured turtles are measured, tagged, and sampled. This study has made it possible to collect information regarding growth rates, sex ratios, genetic structure, and seasonal distributions. In addition, the project provides estimates of abundance and demographic parameters (such as survival, recruitment, emigration, and immigration) needed to construct accurate population assessments. Since 2004, an additional component of this project has involved outside collaborations to measure physiological variables in wild juvenile loggerhead sea turtles to develop baseline health indices and examine seasonal and multiple year trends. In-water sea turtle monitoring is also being conducted by a university led effort in the Mosquito and Indian River Lagoon system on the east coast of Florida. In addition, a number of nesting beach surveys are in place that provide important information regarding survival and trends in nesting populations. All data currently being collected by these studies are valuable baseline information against which to assess the health of future populations in the face of changing climate regimes.

The data yielded by the various aspects of both of these long-term programs assist with determining the current status of sea turtle populations, which in turn provides a benchmark against which to detect future changes that may occur in response to environmental pressures, including climate change.

Research Needs

1. *In situ* ecological community studies of the warm-temperate waters off the SE coast are needed. As invasive species (e.g., lionfish) successfully establish populations, the potential for them to alter the native community assemblage increases, especially as climate change leads to more favorable environmental conditions. There is a need to collect baseline data for fishes, corals, algae, and other invertebrates to quantify changes attributed to these invasions. Repeated sampling of the warm-temperate community, at a variety of inshore and offshore locations, will establish a baseline of community assemblage structure and will allow any community shifts to be detected in the face of natural background inter-annual variability. By monitoring cryptic and small taxa in addition to more conspicuous ecosystem inhabitants, researchers may be able to elucidate phase shifts and ecosystem flips that are difficult to quantify. This would improve our understanding of ecosystem structure, help identify essential fish habitat (with regards to food, cover, spawning, nursery, etc.) and assist in the conservation and management of fishery resources throughout the region.
2. Studies on biology, reproduction and ecology of all invasive species, including lionfish, are needed to better understand the role of climate change in the success or failure of attempts to establish invasive populations.
3. New observational oceanographic process studies are needed to better understand how future climate change will affect fisheries issues. For example, the linkage between larval distributions and ocean currents could be examined by interdisciplinary field operations in critical areas.
4. Numerical models will be critical to providing an understanding of the interconnection between meteorological forcing, ocean conditions and currents, and fisheries issues as the climate changes. Observations will also be needed for calibration and validation of these numerical models before they can be used in a predictive mode.
5. Additional in-water sea turtle research programs located in inshore, nearshore, and offshore areas along the Atlantic and Gulf coasts are needed. Only through increased effort will it be possible to establish a solid baseline of knowledge regarding sea turtle population characteristics and distribution against which potential changes, including those brought about by climate change, can be detected.

Resource Needs

Scientists at the Beaufort Laboratory are currently monitoring invasive lionfish occurrence and abundance at 12 hardbottom stations off North Carolina. This number of stations should be increased and funds provided to ensure regular long-term monitoring at these sites. Sampling should be initiated at inshore sites, where reduced temperature variability resulting from climate change is most likely to lead to increased establishment of lionfish and increased chances of human encounter. Collection of bottom seawater temperature data at a larger number of offshore and inshore stations is necessary to predict the potential range expansion of invasive species in light of climate change. Additionally, monitoring of south Florida reefs for potential establishment of other invasive species documented there by Semmens et al. (2004) should be initiated, along with increased collection of seawater temperatures. This effort would leverage ongoing efforts that document instances of coral bleaching and disease throughout the Florida reef tract.

Additional resources (personnel and research dollars) are needed to continue and expand the type of extended larval/juvenile fish sampling (e.g., Beaufort Bridge net survey) necessary to document changes in life history parameters (growth rates, reproductive timing) that may be affected by changing climate.

Existing in-water sea turtle surveys in North Carolina provide essential demographic information, but due to lack of full time personnel and funding, it has not yet been possible to determine specific habitat requirements and usage patterns for the sea turtle species inhabiting this area. Such information is vital for providing a baseline against which future impacts due to climate change can be compared. Expanding the geographic scope of in-water surveys is equally critical if we are to obtain data that can provide a true picture of sea turtle population status and trends. Success of current and future in-water projects is contingent upon commitment of additional funds, particularly to support permanent employees that can provide program continuity and can also address additional research questions that existing staff have not yet been able to investigate.

Additional funding to cover costs of telemetry (satellite, radio, and sonic) and habitat sampling equipment, as well as research vessel use, is also needed. Of particular interest in North Carolina is the establishment of an acoustic detection array of wireless radio-linked hydrophones whose components could detect turtles outfitted with sonic tags operating within a certain range of frequencies (e.g. Grothues et al., 2005). Given that access to North Carolina's extensive inshore sound system is limited to a small number of inlets, positioning detection buoys at key locations within the sounds, as well as the inlets, would yield invaluable information regarding residency and habitat use. At least one other such acoustic array is already operational along the east coast of the U.S. (Grothues et al., 2005) and therefore if turtles tagged in North Carolina migrate to locations in the vicinity of other arrays, they would also be detected there.

Climate Information Needs

1. Bottom temperature data is the limiting factor in the expansion of invasive species such as lionfish to inshore areas (Kimball et al., 2004). Enhancement of our capability to predict lionfish range expansion into inshore areas requires the increased collection of bottom temperature data into more inshore stations. Bottom temperature data is also needed to understand the ecosystem dynamics of important fishery species (e. g., shrimp, flounder) in the northern Gulf of Mexico under climate change scenarios.

2. Analyses of the effects of climatic conditions on sea turtle distribution require continuing access to environmental data such as sea surface temperature, tidal patterns, and the presence, absence, and nature of major current systems and eddies.

References

Cervino J. M., R. L. Hayes, S. W. Polson, S. C. Polson, T. J. Goreau, R. J. Martinez and G. W. Smith. 2004. Relationship of Vibrio species infection and elevated temperatures to yellow blotch/band disease in Caribbean corals. Applied and Environmental Microbiology 70: 6855–6864.

George, R. H. 1997. Health problems and diseases of sea turtles. In: Biology of Sea Turtles, vol. I (eds. P. Lutz and J. Musick,). CRC Press, Boca Raton, p. 363.

Grosholz, E. D., G. M. Ruiz, C. A. Dean, K. A. Shirley, J. L. Maron and P. G. Connors. 2000. The impacts of a nonindigenous marine predator in a California bay. Ecology 81: 1206-1224.

Harms, C. A., G. A. Lewbart, J. Beasley, A. M. Mexas, T. L. Reynolds, D. E. Malarkey, and L. H. Herbst. 2004. Fibropapillomas in loggerhead sea turtles in North Carolina, USA. 24th Annual Symposium on Sea Turtle Conservation and Biology, San Jose, Costa Rica, 22-29 February.

Jones R. J., J. Bowyer, O. Hoegh-Guldberg and L. L. Blackall. 2004. Dynamics of a temperature-related coral disease outbreak. Mar. Ecol. Prog. Ser. 281: 63-77.

Kimball, M. E., J. M. Miller, P. E. Whitfield and J. A. Hare. 2004. Thermal tolerance and potential distribution of invasive lionfish (Pterois volitans/miles complex) on the east coast of the United States. Mar. Ecol. Prog. Ser. 283: 269-278.

Limpus, C. J. and N. Nicholls. 1988. The Southern Oscillation regulates the annual numbers of green turtle, *Chelonia mydas*, breeding around northern Australia. Australian Wildlife Research 15(2): 157-161.

Marshall, P. A., and H. Z. Schuttenberg. 2006. A Reef Manager's Guide to Coral Bleaching. Great Barrier Reef Marine Park Authority, Australia (ISBN 1-876945-40-0).

Miller, J., R. Waara, E. Muller, and C. Rogers. 2006. Coral bleaching and disease combine to cause extensive mortality on reefs of the US Virgin Islands. Coral Reefs 25:418.

Muller, E. M., C. S. Rogers, A. S. Spitzack, and R. S. van Woesik. 2008. Bleaching increases likelihood of disease on *Acropora palmata.* Coral Reefs 27:191-195.

Patterson K. L., J. W. Porter, K. B. Ritchie, S. W. Polson, E. Mueller, E. C. Peters, D. L. Santavy, and G. W. Smith 2002. The etiology of white pox, a lethal disease of the Caribbean elkhorn coral, *Acropora palmata*. Proceedings of the National Academy of Sciences, USA 99: 8725-8730.

Saba, V. S., P. Santidrian-Tomillo, R. D. Reina, J. R. Spotila, F. V. Paladino, J. A. Musick, and D. A. Evans. 2006. ENSO determines the reproductive frequency of eastern Pacific leatherbacks. In: Book of Abstracts. Twenty Sixth Annual Symposium on Sea Turtle Biology and Conservation (compilers M. Frick, A. Panagopoulou, A. F. Rees, and K. Williams). International Sea Turtle Society, Athens, Greece, p. 355.

Semmens, B. X., E. R. Buhle, A. K. Salomon, and C. V. Pattengill-Semmens. 2004. A hotspot of non-native marine fishes: evidence for the aquarium trade as an invasion pathway. Mar. Ecol. Prog. Ser. 266: 239-244.

Shiganova, T. A. 1998. Invasion of the Black Sea by the ctenophonre *Mnemiopsis leidyi* and recent changes in pelagic community structure. Fish Ocean. 7: 305-310.

Verlaque, M. and P. Fritayre. 1994. Mediterranean algal communities are changing in face of the invasive alga *Caulerpa taxifolia*. Oceanol Acta 17: 659-672.

Witzell, W. N., and T. Azarovitz. 1996. Relative abundance and thermal and geographic distribution of sea turtles off the U.S. Atlantic Coast based on aerial surveys (1963-1969). NOAA Tech. Memo. NMFS-SEFSC-381. National Marine Fisheries Service, Miami, Florida.

California Current Ecosystem

Authors:
William Peterson
(Northwest Fisheries Science Center)
Franklin Schwing
(Southwest Fisheries Science Center)

Introduction

The California Current Ecosystem (CCE) is designated by NOAA as one of eight large marine ecosystems (LMEs) within the U.S. exclusive economic zone. However, the CCE is typified by latitudinal gradients in both physical forcing and biological response. The northern end of the current is dominated by strong seasonal variability in winds, temperature, upwelling, plankton production and the spawning times of many fishes, whereas the southern end of the current has much less seasonal variability in these parameters. For some groups of organisms, the northern end of the CCE is dominated by sub-arctic boreal fauna whereas the southern end is dominated by tropical and sub-tropical species. Faunal boundaries, i.e., regions where rapid changes in species composition are observed, are known for the waters between Cape Blanco Oregon and Cape Mendocino California, and in the vicinity of Point Conception California. Higher trophic level organisms often take advantage of the strong seasonal cycles of production in the north by migrating to the region during the summer to feed. Animals exhibiting this behavior include pelagic seabirds such as black-footed albatross and sooty shearwaters, fishes such as Pacific whiting and sardines, and humpback whales.

Climate and ecosystem studies in the North Pacific have been assigned a high priority by NOAA because climate signals in this region are quite strong. During the past 10 years, the North Pacific has seen two El Niño events (1997/98, 2002/03), one La Niña event (1999), a four-year climate regime shift to a cold phase from 1999 until late 2002, followed by a four-year shift to warm phase from 2002 until 2006. The response of ocean conditions, plankton and fish to these events is well documented in the scientific literature. The biological responses are often so strong that the animals themselves give an early warning before such shifts are noticed in the physical oceanographic records.

Climate Induced Ecosystem Concerns

In the CCE, numerous climate stressors (e.g., warming, sea level rise, freshwater flow) impact productivity and structure throughout the ecosystem. It is difficult to isolate the effect of individual stressors on most individual species, and most of these stressors impact many species at multiple trophic levels. Overall, the climate-species linkages in the CCE are extremely complex. With this caution, we highlight the most important climate-induced concerns below, and identify species or species groups that reflect the response of the system to those concerns. The five issues of greatest concern in the CCE are:

I. Increased variability in climate forcing
II. Changes to the magnitude and timing of freshwater input

III. Changes in the timing and strength of the spring transition and their effect on marine populations
IV. Ocean warming and increased stratification and their impact on pelagic habitat
V. Changes in ocean circulation and their impact on species distribution and community structure

I. Increased variability in climate forcing

Description

One of the likely consequences of global climate change will be a more volatile climate with greater extreme events on the intraseasonal to interannual scales. For the CCE this will mean more frequent and severe winter storms, with greater wind mixing, higher waves and coastal erosion, and more extreme precipitation events and years, which would impact coastal circulation and stratification. Increased variability in physical forcing could translate into problems for living marine resources of the CCE. For example, in the Pacific Northwest the summer of 2005 was characterized by a three-month delay to the start of the upwelling season resulting in a lack of significant plankton production until August (rather than the usual April-May time period). Thus fish, birds and mammals that relied upon plankton production occurring at the normal time experienced massive recruitment failure. In contrast, the summer of 2006 had some of the strongest upwelling winds on record yet many species again experienced recruitment failure, in part because there was a one-month period of no winds (mid-May to mid-June) that occurred at the time when many bird and fish species are recruiting. The northern California Current appears to have recovered from the two summers of poor productivity -- the ocean was cold during the winter of 2006-07, the spring transition to upwelling conditions was very early (February), and zooplankton biomass returned to levels not seen since summer of 2004.

Some global climate models predict a higher frequency of El Niño events, while others predict the intensity of these events will be stronger. If true, primary and secondary production will be greatly reduced in the CCE, with negative effects transmitted up the food chain.

Most models project roughly the same timing and frequency of decadal variability in the North Pacific under the impacts of global warming. However, combined with the global warming trend, the CCE is likely to experience a greater frequency of years consistent with historical periods of lower productivity, e.g., positive Pacific Decadal Oscillation (PDO) values. We know from ongoing observations that a positive PDO (corresponding to warmer ocean conditions in the California Current) results in dominance of small warm-water zooplankton (which are lipid-depleted) which may result in food chains with lower bioenergetic content. By about 2030, it is expected that the minima ocean temperatures due to decadal variability will be above the historical mean of the 20th Century (i.e., the greenhouse gas warming trend will be as large as natural variability).

Current Activities

Studies by NMFS scientists at NWFSC and SWFSC encompass ecosystem-scale data collection, assessments and forecasts. Research includes assessing, understanding and predicting the effects of climate and environmental variability on the production of living marine resources, ecosystem structure and ecosystem function.

Numerous sea-going observation programs contribute to our understanding of living marine resources, their environment, and relationships to climate variability. There are a number of surveys focused on particular fisheries, including surveys for pelagic fish (Northern Anchovy and Pacific Sardine), juvenile salmon, Pacific whiting, pre-recruit rockfish and other groundfish, and adult groundfish. There are also surveys of protected marine species, including surveys for west coast cetaceans, coastal pinnipeds, coastal cetaceans, gray whales, and coastal leatherback turtles and their jellyfish prey. In addition, some surveys document ocean conditions through hydrographic measurements and sampling of plankton, euphausiids, and larval fish (Figures 1 and 2). The CalCOFI surveys of the southern California Current pelagic ecosystem conducted in cooperation with Scripps Institution of Oceanography and California Department of Fish and Game have been conducted continuously since 1949, making this an invaluable record of climate variability in the CCE, particularly for temperature and salinity changes (DiLorenzo et al., 2005) and euphausiids (Brinton and Townsend, 2003). Data from many of these observation programs are being integrated to provide a comprehensive view of the CCE and for distribution to constituents through publications and web pages (e.g. Peterson et al., 2006b; http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm).

Research being conducted at the Northwest Fisheries Science Center that relates to climate and ecosystems includes studies of the oceanographic factors that lead to harmful algal blooms in coastal waters off Washington (in particular in waters within and adjacent to the Olympic National Marine Sanctuary) with an eye towards determining if a warmer and more stratified ocean will lead to increased incidence of HABs. Research has begun on causes of hypoxia in the central Oregon “dead zone” to determine its potential impact on zooplankton – does low oxygen kill eggs of krill and copepods? If so, the dead zone could have a large impact on zooplankton production. Related to this, research continues on the dependence of copepod and euphausiid production rates on phytoplankton blooms. Finally, research is focused on determining the potential impacts of climate change on juvenile salmonids both in their natal freshwater streams as well as in the ocean – top-down and bottom-up effects on salmon growth and survival are emphasized both in freshwater as well as in the ocean. The need for freshwater studies is outlined in the next section of this report.

Scientists in the Southwest Fisheries Science Center are involved in a variety of areas of research concerned with how climate influences on the ocean environment affect the dynamics of marine resources. Beginning in 1986, standardized annual midwater trawl surveys provided information on the abundance and distribution patterns of pelagic juvenile rockfish off central California in relation to their habitat. Research on the ocean ecology of juvenile salmon off California determines interannual variability of juvenile salmon physiology and the influences of biotic and abiotic environmental factors. Advanced survey technologies, including acoustics and submersibles, employ non-intrusive *in situ* survey techniques to perform stock assessments and abundance estimates of several stocks, including endangered populations. Telemetered tagging of highly migratory and anadramous species allow tracking of these animals and mapping their environment. Ship surveys assess the abundance and distribution of marine mammals and to characterize the pelagic ecosystem off the U.S. West Coast. Aerial censuses of pinnipeds monitor trends and abundance of CCE populations.

The Pacific Coastal Ocean Observing System (PaCOOS, http://www.pacoos.org/) has been established to integrate and provide the ecosystem observations and information needed for management of fishery resources, protected marine mammals, marine birds, and turtles, and to forecast the ecosystem consequences of fisheries removals, environmental variability and climate change in the CCE.

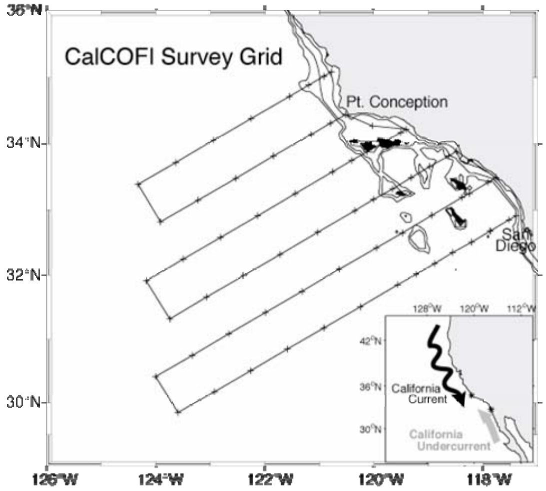

Figure 1. Location of regular CalCOFI survey grid. This grid has been sampled since 1984 on a quarterly basis.

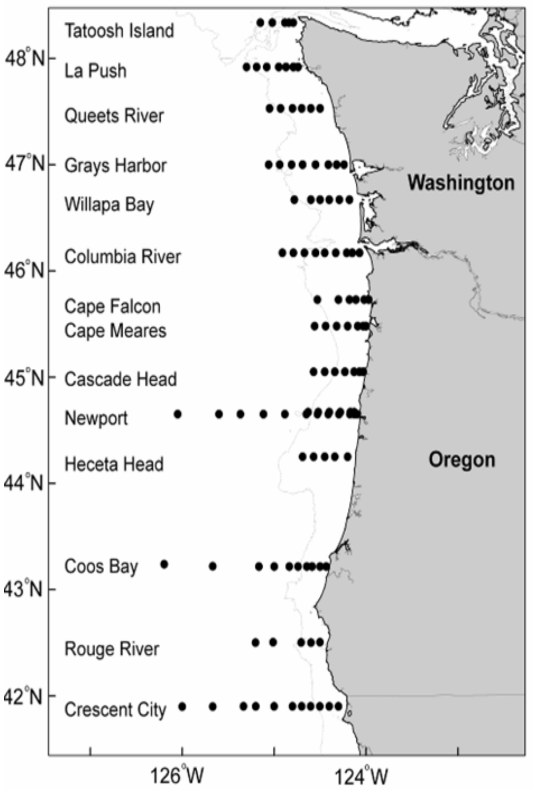

Figure 2. Location of Newport Line (at 44°40'N) that has been sampled for hydrography and zooplankton biweekly since 1996; location of broad-scale survey transects sampled by the Bonneville Power Administration supported program in May, June and September for hydrography, zooplankton and salmon since 1998; location of transects south of Newport sampled for hydrography and zooplankton (1998-2003) and salmon (2000, 2002), and by PaCOOS when NOAA ships become available.

NMFS efforts in the CCE include a wide variety of modeling activities. Stock assessments are conducted for those fishery populations managed by the Pacific Fisheries Management Council, and for a number of marine mammals and sea turtles. Diagnostic studies use individual-based models, lower trophic level and statistical models, and more complete coupled physical-biological and ecosystem models to understand trophic relationships and to develop indicators of environmental variation. Ecosystem models, such as Atlantis, are now being applied to simulate the California Current fishery ecosystem, examine fisheries management options, and project the ecological impacts of climate change. With genetic models, researchers are looking at population structure and dispersal. In general, however, these models are only beginning to consider the influences of climate variability in their assessments and forecasts.

In addition to traditional stock assessments, NMFS scientists are developing and distributing a variety of data products and assessments. The long tradition of developing data bases and conducting research on west coast fishery-related effects of natural environmental variability is being refocused to incorporate aspects of anthropogenic climate change. A number of projects, supported by the NMFS Fisheries and the Environment (FATE) program, are developing and evaluating leading ecological indicators for west coast populations, including salmon, hake, rockfish, and small pelagics, and the lower trophic levels that are the forage base for these populations. These products are being developed in the context of an ecosystem approach to fisheries management, and specifically as indicators for the CCE Integrated Ecosystem Assessment (IEA) process.

Research Needs

A workshop was convened November 2006 in La Jolla, CA focused on climate impacts on the California Current ecosystems. 45 academics and 15 state and federal employees from various west coast institutions attended the workshop. A science plan was developed based upon the workshop discussions. The plan emphasized the development of the ability to forecast the response of lower trophic level organisms and living marine resources to climate variability and change through increased frequency of physical and biological observations in the California Current, and through development of better coupled physical-biological models of the Current. The elements and products of that plan are as follows:

- Develop wind-driven coupled physical-biological models.
- Coordinate coast-wide observations and data sets that improve model validation.
- Forecast recruitment of zooplankton and pelagic fish species 6-12 months in advance, based on data from long-term observing systems and atmospherically forced coupled physical-biological oceanographic models.
- Develop and evaluate ecological indicators and integrated ecosystem assessments that describe the state of the California Current, in collaboration with the NOAA FATE program.
- Increase simulation modeling efforts to address climate change impacts to the CCE. Moreover, efforts need to be initiated that seek to downscale global climate models to regional and local conditions. Specific classes of regional models that are needed include coupled physical-biological models, individual based models of zooplankton and euphausiids, and ecosystem modeling.
- Develop regional scenarios of ecosystem response to climate change based on climate-driven ecosystem models that are run in an “if-then” mode.
- Provide data and information for the pilot Integrated Ecosystem Assessment (IEA) of the California Current, one of the NOAA Regional Priority Areas.
- Provide web-based access to data, model output, and reports which assess the status of the California Current for selected regions. Examples include reports prepared in British Columbia and Newport and that are available at http://www.pac.dfo-mpo.gc.ca/sci/psarc/OSRs/Ocean_SSr_e.htm and http://www.nwfsc.noaa.gov/research/divisions/fed/oeip/a-ecinhome.cfm
- Conduct annual “State of the California Current” stakeholders meetings.

Resource Needs

The greatest needs are for funds to maintain on-going long-term observation programs (e.g., ship-based surveys conducted in the Southern California Bight, Monterey Bay, Arcata, and Newport), glider surveys off S. California, Oregon and Washington, and CODAR stations (which measure surface currents off Oregon and California). The latter two efforts (gliders and

CODAR) have begun to be funded through the Regional Associations (discussed below), however ship-based surveys continue to struggle.

The CCE is covered by three of the eleven geographically distinct members of the National Federation of Regional Associations that comprise the coastal ocean component of IOOS. These are the Northwest Association of Networked Ocean Observing Systems (NANOOS, http://www.nanoos.org/), the Central and Northern California Ocean Observing System (CeNCOOS, http://www.cencoos.org/), and the Southern California Ocean Observing System (SCOOS, http://www.sccoos.org/). These Regional Associations (RAs) are comprised of NOAA and other federal, state and local agencies, academic institutions, non-government organizations, resource managers, and industry, and coordinate ocean observing activities and apply regional solutions to societal problems. They are key in integrating and leveraging ongoing work. The three west coast RAs have received multi-million dollar awards from NOAA to support modeling, moorings, CODAR and modeling of the coastal part of the California Current. Missing are funds to support biological observations programs.

Climate Information Needs

Climate information needed for the California Current ecosystem concerns will come from four categories of NOAA climate data: i) climate data archived at NODC and NCDC, ii) global and regional monitoring, iii) coupled biophysical models, and iv) climate products and forecasts.

Climate data

- Climate data and products from NOAA data centers are needed to provide the climate forcing and environmental context for characterizing and understanding climate impacts on the CCE. These data allow critical retrospective analyses to study past climate variability and forcing for coupled models.
- Climate data and information is needed as the basis for developing science-based operational indicators for resource managers to implement climate variability to decision and policy making. Particular to this concern is the need to adequately describe conditions during interannual (e.g., ENSO) and decadal extremes.
- Continuity of satellite data and products is vital to provide full, high-resolution spatial coverage of important forcings and indicators of state – winds, SST, altimetry, currents, and ocean color.

Monitoring

- Large-scale monitoring (e.g., ARGO) will provide gyre-scale circulation that drives regional circulation, material transport, and the distribution of source waters. Variability in basin circulation and in source waters which feed the California Current related to climate change is responsible for much of the forcing of the CCE.
- Because ecological interactions occur near the coast and on small spatial scales, better monitoring in the coastal region is needed.
- Maintaining NDBC monitoring and data archives will ensure information about regional climate forcing.

Models

- Modeling of climate and atmospheric and oceanic physics needs to be linked with similar work being carried out by NOAA and its partners. NOAA GFDL is working to build coupled physical-biological models as part of an Earth System Model, so there is potential for collaboration. The GFDL global climate model is particularly attractive because it is able to simulate the PDO and other key climate variability signals. Another strong area of collaboration will be with NOAA NCEP's environment modeling activities.

Climate products and forecasts

- Indicators and indices of climate variability (e.g., SOI, PDO) are needed as proxies for quantifying the state and tendency of climate forcing and environmental conditions.
- Seasonal and longer-term forecasts and projections are necessary for forcing coupled physical-biological models and implement into management strategies and stock recovery plans. Seasonal climate forecasts (NOAA OAR ESRL) and models will be needed to couple to ecological models for seasonal population forecasts. They will be critical components of Integrated Ecosystem Assessments, and may ultimately be useful in adjusting fishing quotas.
- ENSO forecasts (NOAA NWS CPC) are useful for projecting future conditions in the CCE, but additional research is needed to understand the mechanisms linking equatorial ENSO processes and teleconnections with California Current conditions and their populations. Not all past El Niño events have had the same impact on the CCE.

II. Changes to the magnitude and timing of freshwater input

Description

The focus is anadramous fish such as salmon that use the Columbia, Klamath and Sacramento River systems. While variability in ocean conditions has substantial impacts on salmon survival and growth, future changes in freshwater and river conditions will likely have a great effect on salmon production.

Warmer air temperatures will result in more precipitation and less snowpack per unit of precipitation. Changes in the seasonal and interannual timing and intensity of rainfall and snowpack, for example, are likely to increase winter and spring runoff but decrease summer runoff. This may change the way the water of the Columbia and Sacramento Rivers is managed for hydropower generation and water storage, which in turn may affect the way salmon and estuarine-dependent species would need to be managed.

Climate models project the 21st Century will feature greater annual precipitation in the Pacific Northwest, extreme winter precipitation events in California, and a more rapid spring melt leading to a shorter, more intense spring period of river flow and freshwater discharge (Figure 3). This will greatly alter coastal stratification and mixing, riverine plume formation and evolution, and the timing of transport of anadramous populations to and from the ocean. Current allocation of western U.S. water resources between salmon and human requirements has been a critical factor in the success of many salmon populations, and will be more so if future water availability is altered.

Likely impacts of climate change on Pacific salmon include the following:

- Altered stream flow and warmer temperatures will reduce the available habitat, life history diversity and freshwater survival rates for juvenile salmon.
- Altered air temperatures will increase heating of mainstem reservoirs and affect juvenile and adult salmon survival and passage timing through sections of regulated rivers such as the Columbia, Klamath, and Sacramento.
- Changes in coastal ocean habitat quality due to changes in productivity and seasonal cycles of production, and food chain bioenergetics.

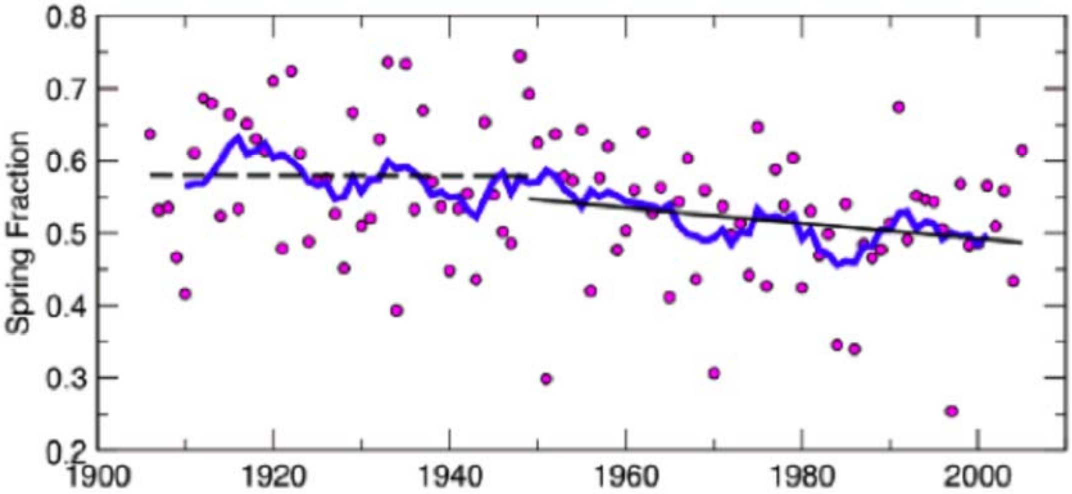

Figure 3. Annual April-July unimpaired runoff in the Central Valley (CA) compared to total annual runoff. Blue curve is nine-year moving average. Dashed line is linear trend prior to 1945; solid line is linear trend after 1945. The reduced April-July runoff is due to a reduced seasonal Sierra snowpack and more rapid melting. (Courtesy of Michael Dettinger, USGS).

Current Activities

1. Since 1998 the Northwest Fisheries Science Center has conducted hydrographic, plankton and pelagic fish surveys in May, June and September. This research program focuses on climate-related interannual variations in abundance of juvenile coho and Chinook salmon, and the variability of their pelagic ocean habitat. One goal is to forecast coho and Chinook returns at least one year in advance, and to determine the influence of climate change on these rates.

2. The Southwest Fisheries Science Center conducts hydrographic and plankton surveys off northern and central California, with a focus on fall Chinook salmon populations that originate from the Sacramento system and coastal rivers. These surveys, in combination with the Northwest Fisheries Science Center studies, will allow study of differences in the response of regional salmon populations to climate change. Of particular interest is the potential for alongshore gradients in temperature and transport in the California Current and the differential response of California stocks as compared to Oregon or Washington stocks.

3. Puget Sound monitoring and modeling studies include juvenile outmigrant sampling along the eastern side of Puget Sound to characterize the seasonal and annual variation in juvenile salmon abundance and size distributions in different riverine, estuarine and nearshore habitats. Information on seasonal habitat use is used to model priority-rearing habitats for protection and restoration under alternative future conditions. Modeling and statistical analyses related to climate impacts on salmon include those highlighting the primary freshwater, estuarine and ocean drivers of salmon population dynamics and diversity and explorations of the effectiveness of protection and restoration strategies on salmon populations in the face of alternative climate futures.

4. Freshwater studies within the Columbia River and its tributaries include prediction of stream flow and temperature changes in Columbia River mainstem and tributaries, evaluation of changes in survival of all Chinook salmon life history types in relation to changes in stream flow and temperature (using rivers with flow diversions as an analogue to rivers affected by climate change), long-term monitoring of juvenile salmon migration and survival in selected tributaries,

through the main stem, and estuary, and development of salmon habitat restoration strategies that are robust to climate change.

5. The Klamath River Chinook salmon assessment is being conducted to improve forecasts of Chinook salmon returns to the Klamath River system. Incorporating climate change via environmental variables into estimates of return abundance of California Chinook salmon may increase the accuracy and precision of these estimates (Wells et al., 2007). Spring ocean conditions have a direct effect on Chinook salmon maturation, and are used to estimate return numbers a year in advance. Freshwater resources in the Klamath basin are critical to Chinook survival (cit.), so variability in stream flow can help forecast adult returns.

Research Needs

A holistic approach to salmon management and salmon recovery efforts, which is focused on the combined effects of climate change on the oceanic and freshwater habitats of Pacific salmon, is needed because (a) global warming will likely have dramatic and predictable impacts on both marine and freshwater ecosystems, and (b) changes in oceanic and freshwater productivity each account for a significant share of the interannual variability in the population dynamics of Pacific salmonids. These stocks have never been studied in such a holistic manner. Success will depend on collaborations between freshwater, ocean and atmospheric scientists. Specifically, we need to:

- Develop a research program to determine how interannual and decadal variations in climate affect simultaneously the coastal ocean ecosystems (where most salmon growth occurs) and the freshwater ecosystems (upon which Pacific salmon rely for spawning and rearing habitats).
- Develop improved understanding of potential responses of Pacific salmon in freshwater and coastal ecosystems to climate-related habitat changes including sea level rise, changes in stream flow and temperature regimes, and shifts in the ENSO cycle and climate indices such as the PDO.
- Identify salmon populations that are most sensitive to climate change, and develop long-term strategies for salmon recovery that are robust to climate change, compatible with societal goals, and meet NOAA’s regulatory mandates for commercial fish and endangered species.

Resource Needs

What is most needed is funding that would bring together a team of NOAA and academic atmospheric, freshwater and marine scientists with expertise in climate modeling, weather prediction and freshwater and marine habitat studies.

Climate Information Needs

- In addition to the information needs described in Concern I, data and models specific to quantifying and forecasting regional precipitation and stream flow patterns is critical.
- Climate information and predictions for watershed and ocean habitats are needed, including observations and predictions of weather patterns, stream flows, snowpack, and ocean properties.

III. Changes in the timing and strength of the spring transition and their effect on marine populations

Description

The focus is on primary and secondary production and the timing of the spring bloom, upwelling, and length of the upwelling season. Sentinel species of concern include zooplankton, krill, sablefish, some rockfish, and sea birds. This is a research focus for the northern and central California Current, where upwelling is strongest.

Phenology is the study of the timing of recurring natural phenomena, and has been principally concerned with the dates of first occurrence of natural events in their annual cycle. In the ecological literature, the term is used more generally to indicate the time frame for any seasonal phenomena, including the dates of first and last appearance of a migratory species. Because many such phenomena are very sensitive to small variations in climate, especially to temperature, phenological records can be a useful proxy for temperature in the study of climate change.

The chief phenological issues for the CCE relate to the onset and length of the upwelling season. The interest is when the upwelling season begins and ends, both physically and biologically (i.e., the spring and fall transitions). These are the onset and end of physical upwelling and when the shelf-slope zooplankton community transitions between a winter-time Davidson current (warm water) community and a spring-summer upwelling (cold water) community. The biological transition times provide an estimate of when seasonal cycles of significant plankton and euphausiid production are initiated.

Coastal upwelling has become stronger over the past several decades due to greater contrasts between warming of the land (resulting in lower atmospheric pressure over the continent) relative to ocean warming. The greater cross-shelf pressure gradient will result in higher alongshore wind speeds and the potential for more upwelling (Bakun, 1990). Regional climate models project that not only will upwelling-favorable winds will be stronger in summer, but that the peak in seasonal upwelling will occur later in the summer (Snyder et al., 2003).

Future climate scenarios indicate greater variability in seasonal climate forcing, which could lead to stronger interannual variability in the timing of the upwelling season. It has also been projected that the onset of seasonal upwelling in spring will be delayed, with a later peak in summer upwelling. Animals (such as whiting, sardines, shearwaters, leatherback turtles, and blue whales) that migrate both to and within the CCE to take advantage of feeding opportunities associated with the seasonal cycle of production, and time their spawning, breeding or nesting with peaks in the seasonal cycles of production, may have to make adjustments in the timing of such activities.

Even though southward winds that cause coastal upwelling are likely to increase in magnitude, these winds may be less effective in driving vertical transport of nutrient-rich water. Given that the future climate will be warmer, the upper ocean at the basin scale will almost certainly be, on average, more stratified. This will make it more difficult for winds and upwelling to mix the upper layers of the coastal ocean, and will make offshore Ekman pumping less effective at bringing nutrients into the photic zone. The result will be lower primary productivity everywhere (with the possible exception of the nearshore coastal upwelling zones).

Finally, should global warming result in shorter winters in the north Pacific, areas where production is light limited, e.g. the northern California Current, may see higher productivity. Phytoplankton blooms are initiated as early as February off northern California in years when storm intensity is low, as has been the case in most years since 2002. These early blooms result in bursts in egg production by both copepods and euphausiids, initiating a cohort of animals that reach adulthood one-two months earlier than a cohort that is initiated with the onset of upwelling in March or April. The result would be a longer plankton production season. Alternatively, regional climate projections are for a later shift in the start time, peak times and end of the upwelling season, which could counter the idea of a longer upwelling season.

Interest in, and awareness of, phenology of organisms in the CCE is very high among fisheries oceanographers because of events observed during the summer of 2005. During that summer, the onset of upwelling was delayed by several months leading to a delay in plankton production. Delayed lower trophic level production was accompanied by (a) a failure of many rockfish species to recruit, (b) low survival of coho and Chinook salmon, (c) complete nesting failure by the sea bird, Cassin's Auklet, and (d) widespread deaths of other seabirds such as common murres and sooty shearwaters. Organisms such as whiting, sardines, shearwaters, and blue and humpback whales that migrate within the CC to take advantage of feeding opportunities associated with the seasonal cycle of production, encountered poor feeding conditions upon their arrival in spring 2005 (Sydeman et al., 2006; Mackas et al., 2006; Schwing et al., 2006; Kosro et al., 2006).

Similar mismatches have occurred in recent years in which upwelling began early (as in 2006 and 2007) but was interrupted at a critical time (May-June). Marine organisms that had come to exploit expected production peaks, found little food. The organisms which seem to be the most affected by delayed upwelling include juvenile salmon that were just entering the coastal ocean in April/May, whiting that were migrating northward, seabirds which are nesting at that time and all other animals that migrate to the northern California Current in summer to feed. Both salmon and seabirds experienced increased mortality in 2006 and 2007, attributed to poor ocean conditions over a relatively short period in late spring.

Current Activities

Ongoing ocean sampling programs that aid in the study of questions related to changes in upwelling and phenology were listed under Concern I, above.

Research Needs

Study of phenology requires precise knowledge of when the upwelling season begins and ends, when marine organisms reproduce, and when migrants arrive at/depart from their feeding grounds. A number of data sets exist (see current activities under Concern 1) which should be analyzed by various techniques to provide insight into these issues. However, to attain high precision, phenological studies will require new observational efforts to collect data routinely at high frequency (preferably daily, although weekly could be acceptable).

In addition, coastal ocean models are needed to provide analysis of upper ocean conditions, including transport of nutrients into the photic zone, and future (synoptic to seasonal) forecasts of coastal upwelling. In combination with the data sets mentioned above, new and improved indices of upwelling should be developed, tested, and made operational. Variations in coastal upwelling can have significant impacts on fish populations and other biological components in coastal ocean ecosystems. Therefore, it is critical to accurately estimate and forecast upwelling and its ecological impacts for the benefit of fisheries and ecosystem management. While existing upwelling indices have been reliable in scores of oceanographic and biological studies, there are limits to their use due to their coarse spatial resolution and the simple application of Ekman theory. Improvements to this index to explain the biological impacts of upwelling can be made in several areas, including: a more realistic and higher-resolved wind product, the inclusion of ocean structure, and short-term predictions based on forecast winds.

Resource Needs

Support for more high frequency field observations of organisms in their environment and data analysis is needed. The most efficient use of resources would be to add more frequent measurements at selected stations which are part of existing observation programs and are convenient to marine laboratories such as off Newport.

Climate Information Needs

Since climate change is likely to affect upwelling in various (poorly understood) ways, we have the following information needs relative to climate change and upwelling response.

- Dates of spring and fall transition, length of upwelling season, overall average magnitude of upwelling, and some measure of the frequency of upwelling events in relation to meanders in the jet stream (sensu Bane et al., 2007). A forecast of the approximate date of spring transition would be useful in forecasting migration and recruitment for many species.
- An index of when the upwelling system has truly transformed from a winter unproductive state to a summer productive state. This will require an index of biological variables.
- Actual measures of the effectiveness of upwelling in terms of the depths from which water upwells, and the nutrient content of that water. A connection between upwelling and stratification will allow study of the biological effectiveness of upwelling.
- Better spatially-resolved coastal wind fields, from satellites or blended measured-modeled products.
- Improved atmospheric models with high-resolution winds, ocean models with upper ocean and coastal circulation and density and nutrients
- Improved regional climate models with projections of the timing, intensity and location of coastal upwelling.
- Ocean models with reliable coastal physics and high resolution to capture Ekman transport and ocean stratification, and can be coupled to biological models to determine phytoplankton production, biomass, subduction, and grazing.
- Forecast models to give short-term and seasonal predictions of wind forcing and upwelling in coastal areas.
- An El Niño/La Niña forecast to assist in determining the timing and strength of upwelling, as well as the quality of source water.

IV. Ocean warming and increased stratification and their impact on pelagic habitat

Description

This concern is focused on the central and southern California Current, and on the organisms that utilize the upper ocean habitat in this region.

Generally warmer ocean conditions will cause a northward shift in the distribution of most species, and possibly the creation of reproductive populations in new regions. Existing faunal boundaries are likely to remain as strong boundaries, but their resiliency to shifts in ocean conditions due to global climate change is not known.

Warmer air temperatures will increase the heat flux into the ocean. Mixing and diffusion are not likely to redistribute this heat rapidly enough to prevent an increase in thermal stability and stratification of the coastal CCE. The vertical gradient in ocean temperature off California has intensified over the past several decades (Palacios et al., 2004) (Figure 4). Roemmich and McGowan (1995) credited this change in temperature structure for the observed long-term decline in zooplankton biomass. Areas with enhanced riverine input into the coastal ocean will also see greater vertical stratification. Moreover, increased melting of glaciers in the Gulf of Alaska coupled with warmer sea surface temperatures will result in increased stratification of the Gulf. Since some of the source waters that supply the northern CC originate in the Gulf of Alaska, more stratified source waters will contribute to increased stratification of coastal waters of the northern CC.

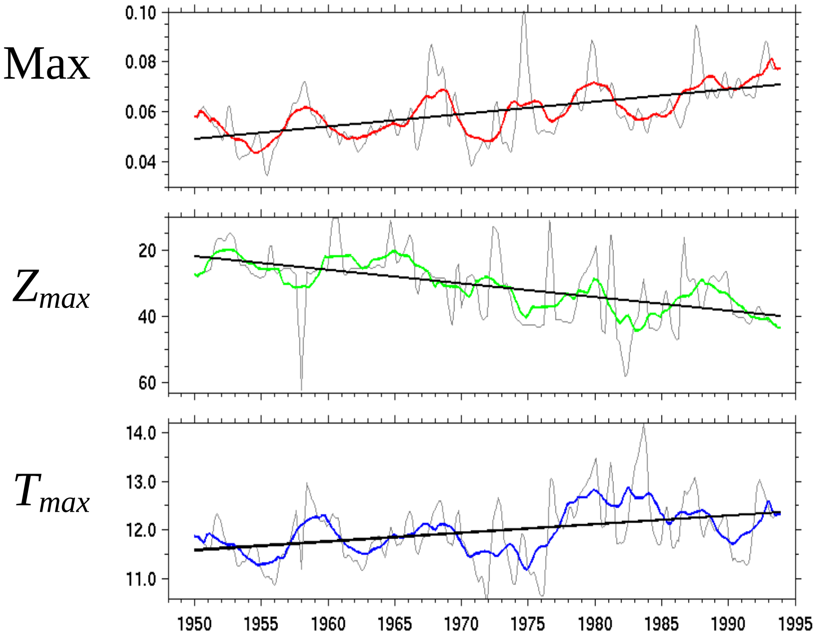

Figure 4. Time series of variables defining stratification in a 1° coastal box off central California (36°N 127°W southwest corner of box), 1950-93. Top panel is maximum vertical gradient in ocean temperature (°C/m), middle panel is depth of maximum gradient (m), bottom panel is temperature at that depth (°C). Light grey curves are monthly series, colored curves are 37-point moving averages. Black lines are linear trend for series. Adapted from Palacios et al. (2004).

The long-term observations program in Monterey Bay is suggesting that as a result of increased stratification, the phytoplankton community is changing from one dominated by diatoms to one dominated by dinoflagellates (Francisco Chavez, MBARI, pers. comm.). Although we do not know what impact this might have on zooplankton grazers, it is clear that diatoms are the primary source of lipids that contribute to lipid- and energy-rich food chains. Dinoflagellates on the other hand are more protein-rich.

Current Activities

Field observations programs were listed under Concern I. Each of those activities has the capacity to investigate how changes in ocean temperatures, water column stratification, and the potential for changes in phytoplankton species will affect sentinel species and other living marine resources through changes in species composition at the base of the food chain.

In addition, recent developments in telemetry and biologging technology have greatly enhanced our ability to enlist apex marine predators to sample their environment. Biologging is a particularly effective observing strategy, as it enables large-scale monitoring of species' ranges and distributions while collecting large quantities of oceanographic data at the scale of the animals' behavior. These animals can be instrumented with electronic tags to identify their critical foraging habitats, migration corridors, and regions of high occupancy, i.e. biological hot spots, and how climate variability affects the distribution, size, and character of these hot spots. The Tagging of Pacific Pelagics (TOPP) program, a Census of Marine Life pilot project, has tagged 23 species in the eastern Pacific and acquired over 200,000 days of data between 2002-06 on species movements and behaviors. From this data set, various regions of the California Current System have emerged as important hot spots for a number of apex predators. How robust these locations are to future climate change is not known.

Research Needs

- Long term surveys must be maintained of coastal pelagic species (e.g. anchovy, sardine, jack mackerel, Pacific mackerel, market squid). The surveys need to cover the geographic spawning range of these species, as well as the geographic dispersion of their juvenile stages, and measure critical environmental variables sensitive to climate variability (temperature, salinity, nutrients, currents, chlorophyll, zooplankton size and species composition).
- Surveys are needed to provide information on the survival of eggs and larvae into the juvenile stages and contribute to estimates of climate influences on recruitment. These surveys also would provide the data necessary to resolve current uncertainties regarding impacts of climate variability on stock structure, migration patterns, geographic variation in vital rates and trophic interactions.
- Because coastal pelagic species respond to climatic forcing, detailed information on their life histories is required to accurately forecast population trajectories.
- Because coastal pelagic species are the forage base for many of the piscivorous fish, marine mammal and seabird populations in the CCE, knowledge of trophic interactions is required to understand their roles in the functioning of the system. Such information is necessary if we are going to be able to predict the likely consequences of depletion of a given forage fish species in the context of climate change.
- Similarly the CalCOFI program, through the PaCOOS program, needs to be expanded to include the surveys off Eureka (CA), Oregon and Washington such that climate-related changes in stratification and lower trophic level organisms can be evaluated within the entire CCE.
- Continued deployments of electronic tags on targeted marine predators are needed to expand our monitoring of temporal variability in species ranges and distributions. These data also provide significant information on the physical structure of the ocean.

Resource Needs

New surveys could be conducted as an extension of the spring and summer (or fall) CalCOFI surveys. The CalCOFI surveys are currently limited to the Southern California Bight (San Diego to Point Conception) with limited coverage further north to San Francisco. Thirty sea days on a second research vessel will be required to provide near-synoptic coast-wide coverage (Baja California to British Columbia). In addition, support for additional sample processing and enhanced data management will be required. Also, funding for increased use of electronic tags on marine predators will be needed.

Climate Information Needs

- In addition to the climate information described in Concern I, this concern requires data on the factors that contribute to upper ocean stratification. These include coastal wind (for estimating wind stress, mixing, and latent heat exchange), air-sea heat fluxes, and streamflow and freshwater discharge throughout the CCE region.
- High-resolution synoptic mapping of ocean variables that define biological “hot spots” must be maintained to monitor changes in the pelagic habitat and relations to climate variability.
- Regional models with reliable precipitation and stream flow projections are necessary to model future coastal pelagic ocean conditions.
- IPCC projections of future temperature and stratification are needed to allow long-term estimates of changes in upper ocean structure and productivity, which will determine the pelagic habitat for many coastal species.

V. Changes to ocean circulation and their impact on species distribution and community structure

Description

This is a climate-induced ecosystem concern primarily for the northern California Current, although changes in transport are known to have subtle effects on the entire Current. A particular biological concern here is variability in the transport of organisms, which impacts zooplankton species composition and regional recruitment patterns for demersal fish stocks.

Decadal variations in regional water mass characteristics such as salinity, nutrients, and chlorophyll are linked to shifts in regional and large-scale circulation (Parrish et al., 2000; DiLorenzo et al., 2008). The circulation of the North Pacific subtropical gyre combines with regional and local upwelling and advection, creating a complex coastal circulation. Basin-scale adjustments in the subtropical gyre due to changing global wind stress curl are thought to be a principal factor in these decadal fluctuations within the CCE, and can explain variations in regional water mass characteristics and related biological variables that are not correlated with surface indicators such as the PDO.

The California Current extends from the northern tip of Vancouver Island, Canada to southern Baja California, Mexico. As the current flows from north to south, the waters warm and mix with offshore waters such that both temperature and salinity increase gradually in a southward direction. Not surprisingly, observations of the biota of the California Current show pronounced latitudinal differences in the species composition of plankton, fish, and benthic communities, ranging from cold-water sub-arctic species in the north to warm-water subtropical species in the south. Changes in abundance and species composition can be gradual in some cases, but it is widely accepted that ocean faunal boundaries (zones of rapid change in species composition) are present in the vicinity of Capes Blanco and Mendocino, and at Point Conception. Strongest contrasts are seen during summer.

A strong contrast in species composition is also seen between the continental shelf and offshore waters during summer, due to the upwelling process. A combination of upwelling and sub-arctic water that feeds the inshore arm of the northern end of the CCE creates conditions favorable for development of a huge biomass of sub-arctic zooplankton. During the cool phase of the PDO, all of the northern CCE becomes more sub-Arctic in character (both shelf-slope-oceanic regions); during the warm phase, the water masses and associated copepod community become more similar to a sub-tropical community. During the warm phase copepod biodiversity increases in coastal waters, due to shoreward movement of offshore waters onto the continental shelf, caused by either weakening of southward wind stress in summer or strengthening of northward wind stress in winter. Thus, when the PDO is in the warm phase, a greater proportion of the water entering the northern end of the Current is sub-tropical in character rather than sub-Arctic.

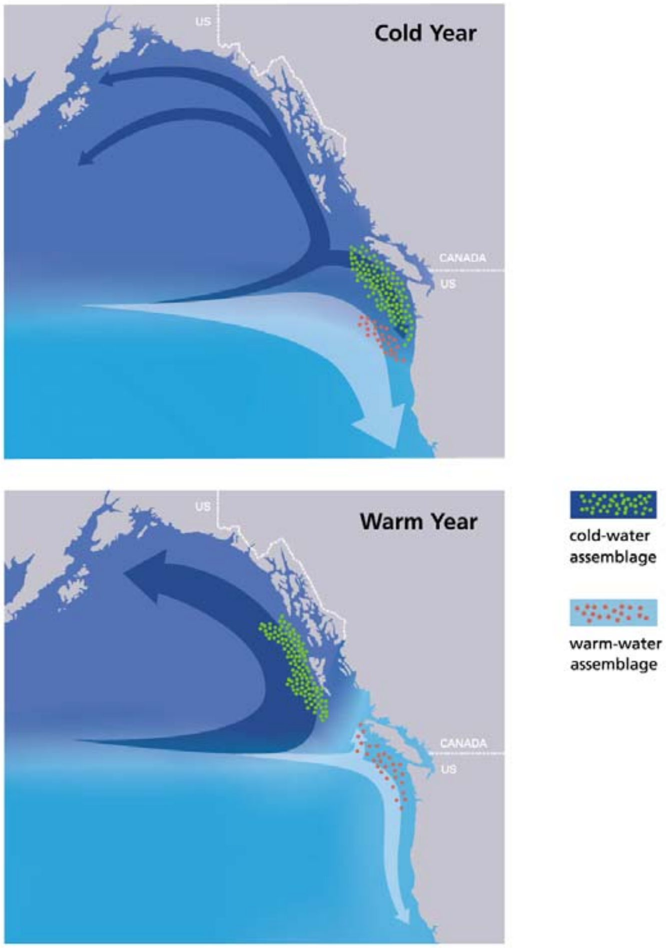

Figure 5. Schematic of the flow of the North Pacific Current south into the California Current and north into the Gulf of Alaska. Cool years (such as La Niña and negative PDO years) are associated with greater flow into the California Current, which favors a southward displacement of cold-water and warm-water species.

Regardless of the season, the source waters that feed into the California Current from the north and offshore can exert some control the over the phytoplankton and zooplankton species that dominate the current (Figure 5). Hooff and Peterson (2006) suggest that knowledge of source waters is critical to understanding ecosystem dynamics in the shelf waters of the Northern CCE because waters from the Gulf of Alaska carry large, lipid-rich copepods to the shelf waters, whereas waters coming from an offshore source carry small, oceanic lipid-poor copepods to the shelf waters. Thus changes reflected by PDO shifts may result in local food chains that have vastly different bio-energetic content. Given, for example, that (a) salmon returns are low when the PDO is in a positive, warm-water phase, but high when the PDO is negative, and (b) salmon returns to Pacific Northwest rivers are highly correlated with copepod community structure (Peterson and Schwing, 2003, Peterson et al., 2006b) variations in the bio-energetic content of the food web may represent a mechanistic link between PDO sign change and salmon survival.

Northward shifts in distribution of zooplankton and fish species are also possible. Generally warmer conditions could result in a northward shift in the distribution of some species, and possibly the creation of reproductive populations in new regions. Examples include Pacific whiting, which migrate farther north during warm summers. A long-term shift toward greater (lesser) abundance of southern (northern) fish (W. Watson, NOAA/SWFSC, personal communication; Peterson et al., 2006a) and intertidal (Barry et al., 1995) species is thought to be due to warmer (cooler) conditions, which in part is the result of reduced (increased) southward transport. Moreover, there is evidence that both whiting and sardines are now spawning in waters off Oregon and Washington (R. Emmett, NOAA/NWFSC, personal communication).

Alternatively, if upwelling strengthens due to global climate change, regardless of the sign of the PDO, cold-water species should still be favored in the coastal upwelling zones. However, the onshore-offshore gradients in temperature and species abundance should strengthen if offshore waters become warmer and upwelling becomes stronger, creating stronger upwelling fronts, and perhaps a greater level of mesoscale activity. It is unclear how faunal boundaries might be affected.

West coast groundfish stocks are characterized by highly variable recruitment, with interannual variation in cohort strength often ranging over two orders of magnitude. This variation in reproductive success is the predominant source of variation in stock productivity, such that knowledge of impending recruitment has the potential to significantly increase the accuracy of stock assessment forecasts and annual catch limits. However, we now know that the coastwide distribution of age-0 pre-recruit rockfish is strongly affected by ocean climate conditions, requiring a large-scale survey to adequately characterize interannual variation in year-class strength. Since 2001, efforts by the SWFSC and the NWFSC have resulted in a coordinated coastwide survey of pre-recruit groundfish (i.e., rockfish and Pacific whiting) that is capable of providing informative indices of impending recruitment. However, this broader scale survey has revealed significant changes in the distribution of young of year (YOY) groundfish, apparently in response to changing ocean conditions. Notably, beginning in 2004 certain stocks of rockfish have developed a more southerly YOY distribution, while others have become increasingly distributed to the north (Steve Ralston, NOAA/SWFSC). These findings provide clear evidence of latitudinal shifts in distribution and ecosystem restructuring and point toward the kinds of biological changes we can expect from climate change.

Another aspect of the local circulation that is thought to be related to zooplankton population abundance and fish habitat size is the level of mesoscale structuring of continental shelf waters, e.g., the level of eddy kinetic energy (EKE) caused by the development of fronts and eddies in the alongshore flow. Initial studies provide some evidence that local levels of EKE in the California Current is related to the PDO (J. Keister and T. Strub, Oregon State University, personal communication), and it has been suggested that the complexity of coastal circulation is related to the speed of the subtropical gyre (U.S. GLOBEC Reports 11 and 17).

Current Activities

See list of monitoring efforts identified in Concern I.

Research Needs

To better understand linkages between climate forcing, transport of the California Current, and changes in food web structure, we need new research that will achieve the following goals:

- Understand the degree to which climate variability leads to variations in the large-scale circulation and source of water transported into the California Current and how these variations may be related to food chain structure (size and bioenergetic content of phytoplankton and zooplankton) and recruitment success of planktivorous fishes in the California Current;
- Use remote sensing data to identify physical oceanographic features (fronts, eddies) that appear to be linked with spatial variation in biological features such as chl-*a*, zooplankton and fish distributions, and determine how climate variability may affect such features.
- Characterize the interannual variations in size of suitable habitat for juvenile rockfish and adult small pelagic fishes, using time series of satellite data and *in situ* observations.
- Develop regional coupled bio-physical models capable of accurately resolving seasonal and longer variability in the large-scale and mesoscale circulation of the California Current and transport of key physical, chemical, and biological components.

To accomplish these four goals, we need to focus on how sub-basin scale winds affect the transport of different water types that enter the northern California Current, using both the altimeter (sea surface height) and QuikSCAT (winds). SST and ocean color data could be applied to identify large scale and mesoscale physical and biological oceanographic features such as fronts and eddies, and when linked to meteorological forcing, should provide a better understanding of the coupling between meteorological events and physical oceanographic features in continental shelf and slope waters off Washington, Oregon and California.

Resource Needs

- Existing long-term surveys must be maintained, especially the central California midwater trawl (juvenile rockfish) surveys, Newport time series and the newly-inaugurated time series at Eureka.
- Expand sardine, anchovy, rockfish and whiting surveys coast-wide where possible.
- Make greater use of data streams from satellites (sea surface height, winds, SST, color).
- Improve models relating transport and water mass type to biology.

Additional staffing will be required as this would allow a more comprehensive evaluation of potential applications of the coast-wide midwater trawl (juvenile rockfish) survey, including characterizing interannual variation in community composition of rockfish as well as micronekton in relation to the ocean environment. Currently, observations aboard the chartered F/V Excalibur, a 65’ trawler, are limited to biological sampling of the catch. Enhanced hydrographic capability aboard that vessel (e.g., CTD casts) would significantly increase our understanding of epipelagic habitat variability over the entire west coast continental shelf and slope during the peak of the upwelling season.

Climate Information Needs

- Water mass climatology and anomaly fields (using water mass characteristics to distinguish water type and sources in near real-time), and satellite and blended satellite-model reanalysis products to provide the details of water sources and transport patterns in near real-time.

- Basin-scale ocean circulation observations and models to determine changes in gyre circulation and source and advection of water mass types.

References

Bakun, A. 1990. Global climate change and intensification of coastal ocean upwelling. *Science* 247: 198-201.

Bane, J. M., Y. H. Spitz, R. M. Letelier and W. T. Peterson. 2007. Jet stream intraseasonal oscillations drive dominant ecosystem variations in Oregon's summertime coastal upwelling system. *Proc. Natl. Acad. Sci.* 104(33): 13262-13267.

Barry, J. P., C. H.Baxter, R. D. Sagarin and S. E. Gilman. 1995. Climate-related, long-term faunal changes in a California rocky intertidal community. Science *267: 672-675.*

Brinton, E. and A. W. Townsend. 2003. Decadal variability in abundance of the dominant euphausiid species in the southern sectors of the California Current. *Deep-Sea Res. II-Topical Studies in Oceanography* 50: 2449-2472.

DiLorenzo, E., A. J. Miller, N. Schneider and J. C. McWilliams. 2005. The warming of the California Current: dynamics and ecosystem implications. *J. Phys. Oceanogr.* 35: 336-362.

Di Lorenzo E., N. Schneider, K. M. Cobb, K, P. Chhak, J. S. Franks, A. J. Miller, J. C. McWilliams, S. J. Bograd, H. Arango, E. Curchister, T. M. Powell and P. Rivere, 2008. North Pacific Gyre Oscillation links ocean climate and ecosystem change. *Geophys. Res. Lett.*, 35, L08607, doi:10.1029/2007GL032838.

Hooff, R. C. and W. T. Peterson. 2006. Recent increases in copepod biodiversity as an indicator of changes in ocean and climate conditions in the northern California current ecosystem. *Limnol. Oceanogr.* 51: 2042-2051.

Kosro, P. M., W. T. Peterson, B. M. Hickey, R. K. Shearman, and S. D. Pierce. 2006. Physical versus biological spring transition: 2005, *Geophys. Res. Lett.,* 33, L22S03, doi:10.1029/2006GL027072.

Mackas, D. L., W. T. Peterson, M. D. Ohman, and B. E. Lavaniegos. 2006. Zooplankton anomalies in the California Current system before and during the warm ocean conditions of 2005, *Geophys. Res. Lett.*, 33, L22S07, doi:10.1029/2006GL027930.

Palacios, D. M, S. J. Bograd, R. Mendelssohn, and F. B. Schwing. 2004. Long-term and seasonal trends in stratification in the California Current, 1950-1993. *Journal of Geophysical Research- Oceans* 109 (C10): C10016, doi:10.1029/2004JC002380.

Parrish, R. H., F. B. Schwing, and R. Mendelssohn. 2000. Midlatitude wind stress: the energy source for climatic regimes in the North Pacific Ocean. *Fish. Oceanogr.* 9: 224-238.

Peterson, W. T. and F. B. Schwing. 2003. A new climate regime in Northeast Pacific ecosystems. *Geophys. Res. Lett.* 30(17), 1896. doi:10.1029/2003GL017528.

Peterson, W. T., R. C. Hooff, C. A. Morgan, K. L. Hunter, E. Casillas and J. W. Ferguson. 2006a. Ocean conditions and salmon survival in the northern California Current. Web Document. http://www.nwfsc.noaa.gov/research/divisions/fed/ecosysrep.pdf

Peterson, W. T., R. Emmett, R. Goericke, E. Venrick. A. Mantyla, S. J. Bograd, F. B. Schwing, R. Hewitt, N. Lo, W. Watson, J. Barlow, M. Lowry, S. Ralston, K. A. Forney, B. E. Lavaniegos, W. J. Sydeman, D. Hyrenbach, R. W. Bradley, P. Warzybok, F. Chavez, K. Hunter, S. Benson, M. Weise, and J. Harvey. 2006b. The state of the California Current, 2005-2006: warm in the north, cool in the south. *Cal. Coop. Fish. Invest.* 47: 30-74.

Roemmich, D. and J. McGowan. 1995. Climatic warming and the decline of zooplankton in the California Current. *Science* 267: 1324-1326.

Schwing, F. B., N. A.Bond, S. J.Bograd, T. Mitchell, M. A. Alexander and N. Mantua. 2006. Delayed coastal upwelling along the U.S. west coast in 2005: a historical perspective. *Geophys. Res. Lett.*, 33, L22S01, doi:10.1029/2006GL026911.

Snyder, M. A., L. C. Sloan, N. S. Diffenbaugh, and J. L. Bell. 2003. Future Climate Change and Upwelling in the California Current, *Geophys. Res. Lett.*, 30, No. 15, 1823, doi:10.1029/2003GL017647.

Sydeman, W. J., R. W.Bradley, P. Warzybok, C. L. Abraham, J. Jahncke, J. D. Hyrenbach, V. Kousky, J. M. Hipfner and M. D. Ohman. 2006. Planktivorous auklet *Ptychoramphus aleuticus* responses to ocean climate, 2005: unusual atmospheric blocking? *Geophys. Res. Lett.*, 33, L22S09, doi:10.1029/2006GL026736.

Wells, B. K., C. B.Grimes, and J. B.Waldvogel. 2007. Quantifying the effects of wind, upwelling, curl, turbulence, and sea surface temperature on growth and maturation of a California Chinook salmon (*Oncorhynchus tscawytscha*) population. *Fish. Oceanogr.* 16: 363-382.

Alaskan Ecosystem Complex

Authors:
Michael Sigler, Jeffrey Napp, and Anne Hollowed
(Alaska Fisheries Science Center)

Introduction

The Alaskan ecosystem complex is comprised of four large marine ecosystems (LMEs): Gulf of Alaska, East Bering Sea/Aleutian Islands, Chukchi Sea and Beaufort Sea. Marine fisheries of Alaska provide almost 50% of the nation's seafood harvest, and this harvest is important to our balance of trade with other countries. The Bering Sea is directly or indirectly the source of over 25 million pounds of subsistence food for Alaska residents, primarily Alaska Natives in small coastal communities (Bering Ecosystem Study, 2004). Alaska's nearly 44,000 miles of coastline constitute about two-thirds of the total U.S. coastline and support a wide variety of habitats and user communities. The region's natural beauty and resident and migratory species are the basis of a billion dollar tourist industry.

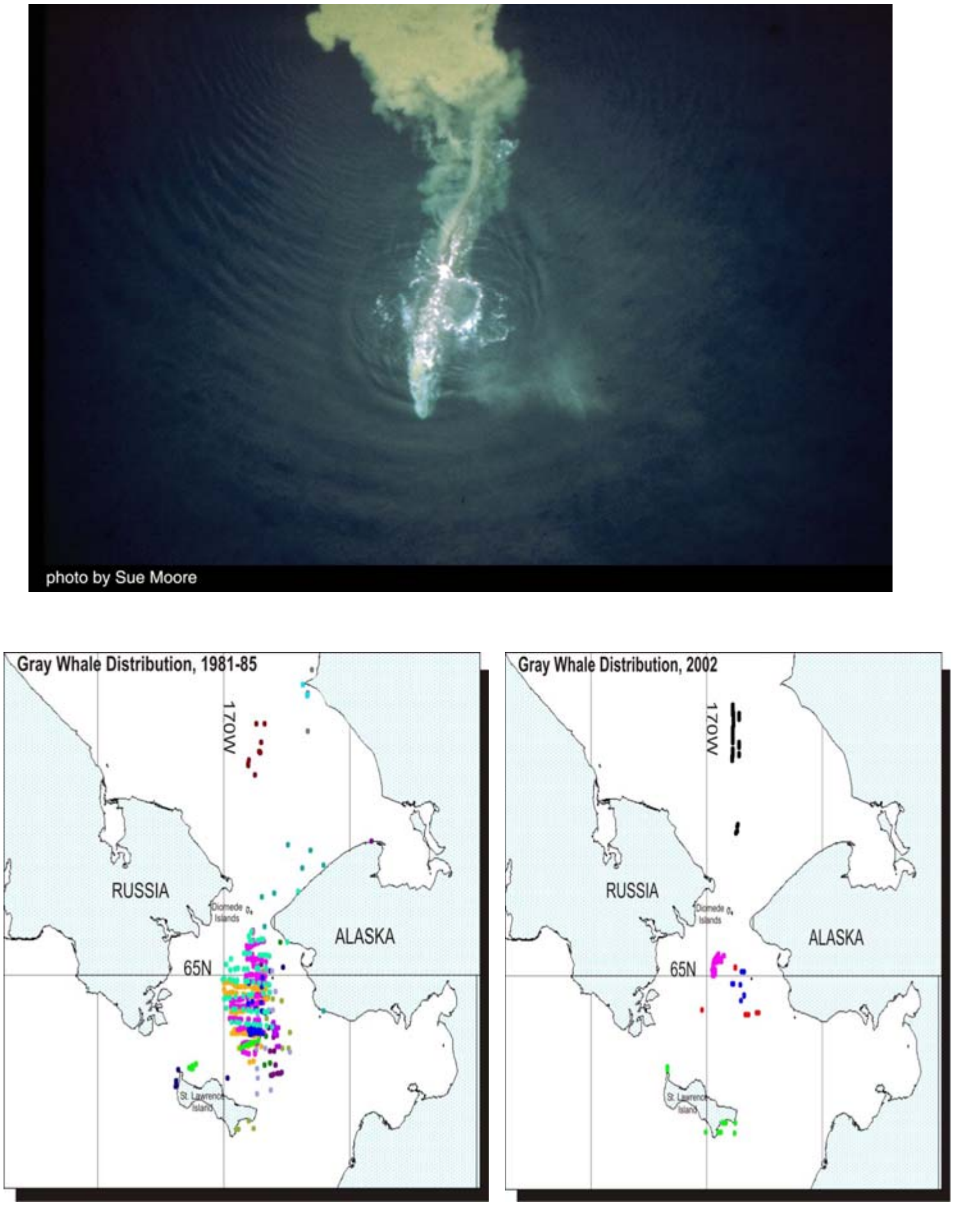

Figure 1. Gray whale feeding grounds have changed. Feeding gray whale (top). Retrospective (left) and current (right) gray whale distribution in the northern Bering Sea. Colors indicate years (left) and days (right). (Moore et al., 2003)

Alaska's marine ecosystems are highly responsive to shifts in climate (e.g. Hare and Mantua, 2000; Hollowed et al., 2001; Connors et al., 2002, Hunt et al., 2002; Moore et al., 2003). As high-latitude, cold oceans, three of the issues highlighted in the Introduction are relevant to these ecosystems: climate regimes and ecosystem productivity, loss of sea ice and ocean acidification. Two of the four LMEs within the Alaskan complex (Bering Sea / Aleutian Islands and Gulf of Alaska) have experienced documented regime or phase shifts in community organization and productivity related to changing climate (Figure 1; Anderson and Piatt, 1999; Ciannelli et al., 2005; Grebmeier et al., 2006; Litzow et al., 2006; Litzow and Ciannelli, 2007; Mueter and Litzow, 2008). Three of the four LMEs are extremely susceptible to loss of sea ice and all four of the LMEs are susceptible to the impacts of ocean acidification. General circulation models predict that the largest changes in global temperatures will occur at high latitudes, and such change has already begun on both land and in the oceans surrounding Alaska (ACIA, 2004; Stabeno and Overland, 2001). At risk are Alaska's seafood production, the recovery of endangered and threatened marine species, the living marine resources that nourish and provide continuity of Alaska's native cultures, and natural resources that support Alaska's large tourism industry.

It is imperative that we develop a mechanistic understanding of how ecosystems respond to climate change to apply in stewardship of our living marine resources. Climate shifts may cause changes in habitat suitability, trophic interactions and community composition through the disappearance or introduction of species. We must evaluate the sensitivity of our management strategies to climate change, mitigate unavoidable changes that adversely impact our stakeholders, and advise our stakeholders on the direction and rate of future changes (e.g. Jurado-Molina and Livingston, 2002).

Climate Induced Ecosystem Concerns

Prudent and informed stewardship of Alaska's living marine resources is challenging due to the high number of large marine habitats, the general remoteness of the region, the lack of knowledge of important factors influencing many of the commercial and subsistence species and the changing of climate conditions. The prioritized major climate related concerns for Alaska's four large marine ecosystems are:

I. Climate regimes and ecosystem productivity (Rank 1)
II. Loss of sea ice (Rank 1)
III. Ocean acidification (Rank 2)

All three concerns are potentially serious climate related threats to Alaska's living marine resources. The magnitudes of these threats likely are similar, with major changes possible. However temperature-related effects are occurring sooner than anticipated ocean pH related effects (e.g., some species already have moved northward); thus we rank the first two concerns slightly ahead of the third concern.

I. Climate Regimes and Ecosystem Productivity

Description

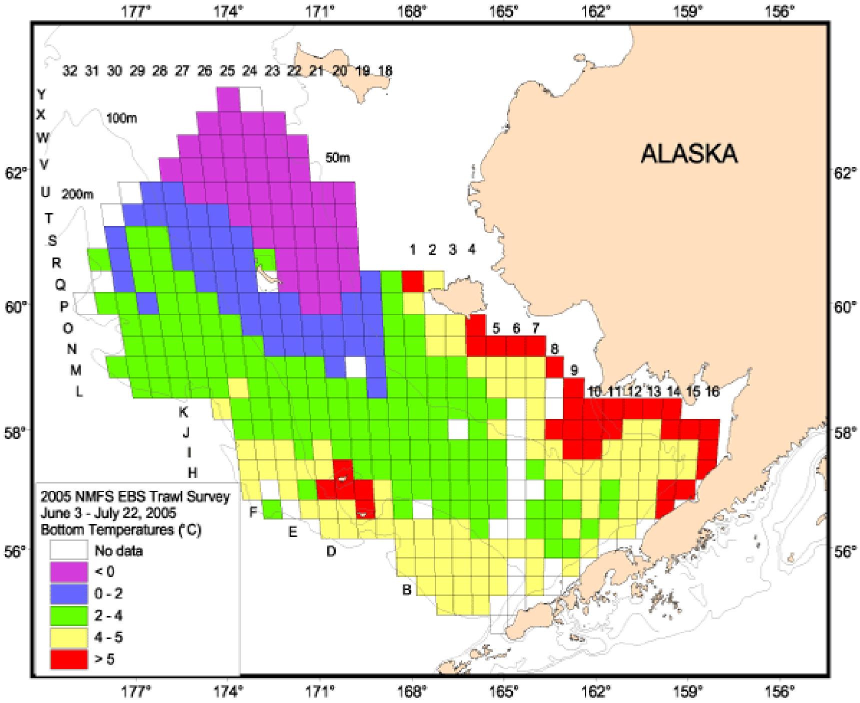

Figure 2. Bering Sea bottom temperatures measured from a bottom trawl head rope. The middle shelf used to be covered with a pool of cold water (< 2°C) from seasonal ice. Now the bottom temperatures are > 2 °C). Courtesy of R. Lauth, AFSC.

Regional weather and climate patterns in Alaska are changing -- there has been an increase in the amount of heat flux to the ocean and land, and a decrease in the amount of wind energy. These two forces, heat and wind, are major structuring elements for our large marine ecosystems. Recent changes in Alaska's coastal waters have been: general warming of ocean surface waters, warming of the southeast Bering Sea bottom waters over the continental shelf (Figure 2), a more strongly stratified ocean, hypothesized decrease in ocean productivity, alteration of pelagic ocean habitat, and changes in the distribution of species. In short, these changes have the potential to affect the structure, function, productivity, and composition of Alaska's marine ecosystems. These changes may have large and irreversible impacts on our fin and shellfish harvests in the eastern Bering Sea / Aleutian Islands and Gulf of Alaska. In addition, changes in the structure, function, and productivity of these ecosystems may negatively impact the protected marine species that live or migrate through these ecosystems (e.g. North Pacific right whale).

Current Activities

North Pacific Climate Regimes and Ecosystem Productivity (NPCREP) is a partnership between the Alaska Fisheries Science Center (AFSC) and NOAA's Pacific Marine Environmental Laboratory (PMEL) that focuses on how changing climate conditions affect the growth, survival, and recruitment of Alaska's fin and shellfish species. Program goals are to reveal the mechanisms of how climate change impacts living marine resources and to provide the knowledge and insight to build models that accurately simulate how changing conditions impact populations. NPCREP is a small, but highly leveraged project begun in 2004. NPCREP contributes essential components of an observation backbone in the eastern Bering Sea. This observation network provides near-real-time observations of upper ocean and meteorological parameters. Data from its ship- and mooring-based observation network are reported in the Ecosystems Considerations chapter of the Stock Assessment and Fishery Evaluation (SAFE) reports (e.g. Boldt, 2006). NPCREP examines how ocean and atmosphere interact to determine the transport of larvae of commercial flatfish species to their nursery grounds (Lanksbury et al., 2007) and collaborates with stock assessment modelers to incorporate climate variability into next generation stock assessment and ecosystem indicators and models. NPCREP supports retrospective studies of how groundfish distributions in the Bering Sea are changing in response to climate (Mueter and Litzow, 2008, Figure 3), and the use of indicators or metrics in an ecosystem approach to management.

Two other programs deserve mention: Fisheries-Oceanography Coordinated Investigations (FOCI, 1984-present) and Fisheries And The Environment (FATE). FOCI is a long-lived NOAA research program conducted jointly by the AFSC and PMEL primarily in the western Gulf of Alaska. FOCI's goals are to understand the climate and ecosystem processes that affect the recruitment of walleye pollock, and to develop models and indicators that advise the Plan Teams and Management Council in setting catch limits (Kendall et al., 1996). FATE, a national program with regional components, applies conceptual models and mechanistic understanding to formulate models capable of predicting future trends in recruitment and stock size and increasing accuracy in assessments of target species.

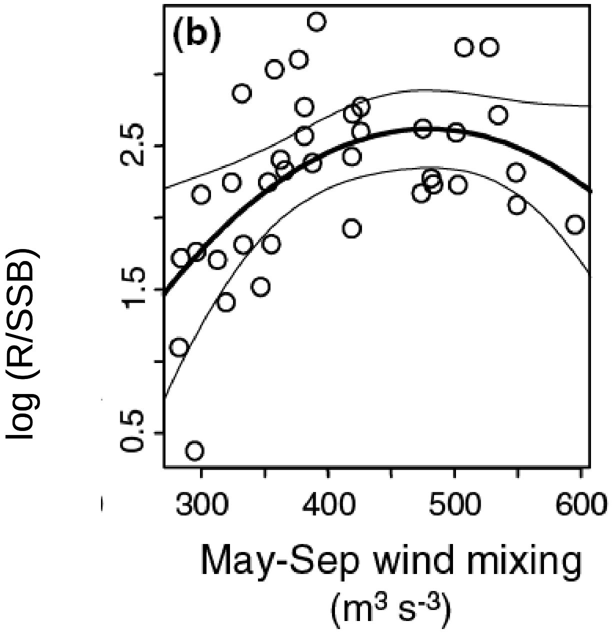

Figure 3. Juvenile survival is maximized when moderate spring and summer winds lead to a generally stable upper water column and periodic renewal of nutrients. Recruits (R) per spawning stock biomass (SSB) vs. May-Sep wind mixing. (Mueter et al., 2006)

Research Needs

NPCREP's focus is currently limited to the eastern Bering Sea. The Alaska Fisheries Science Center is responsible for applying an ecosystem approach to management in four large marine ecosystems, and at present NPCREP's funding limits our joint research with PMEL to only one of the four. NPCREP focuses on measuring physical and biological processes at lower trophic levels that affect fin and shellfish recruitment.

Priorities within the eastern Bering Sea ecosystem are:

- Maintain/expand the observation system (moorings). The NPCREP Bering Sea observational network is anchored by (4) biophysical moorings along the 70 m isobath. We have begun to supply data from the moorings to our stakeholders in near real time and propose to expand this effort.
- Expansion of process studies to include juvenile fish. The juvenile stage of fishes, particularly flatfish, can be a recruitment bottleneck. The eastern Bering Sea supports commercial fisheries for several flatfish species, some of which appear to respond to changes in climate (Wilderbeuer et al., 2002; Lanksbury et al., 2007). We need to

understand if the recruitment bottlenecks are in the larval or juvenile phase. NPCREP and stock assessment scientists are collaborating to incorporate our knowledge of larval behavior and distribution into models that predict larval transport and whether transport will cross favorable nursery areas.

- Full implementation of ecosystem modeling efforts. NPCREPs bottom up approach to climate-induced effects requires a full 3-D coupled biophysical model. NPCREP and North Pacific Research Board funding has been used to construct the initial model. Continued use and improvement (adding more trophic levels) will require additional funding. The next step is to introduce physical forcing consistent with IPCC projections into our models and observe the simulated effects on commercially important fish species.
- Ability to support multiple extramural metrics/indices projects each year and hold annual synthesis meetings. The program has only been able to support one extramural metric/indices or modeling project in most years. We need to accelerate our progress in this area to develop new metrics that track the health and status of the eastern Bering Sea. In addition, we have plans to begin annual synthesis meetings to help bring panels of experts together each year to interpret and synthesize climate-induced changes in the eastern Bering Sea. These synopses will be reported in the Ecosystems Considerations Chapter of the Council's SAFE document.

Missing is geographic expansion of NPCREP's efforts to other Alaska LMEs. While the Bering Sea is the most productive Alaska ecosystem in terms of commercial fisheries, the Gulf of Alaska and Chukchi and Beaufort Seas have important living marine resources that respond to changes in climate. Addressing climate induced change in these other systems is a high priority, but must wait until we can fully implement NPCREP in the eastern Bering Sea.

Resource Needs

NPCREP funding levels are well below what was originally proposed for a fully functional program in both the Bering Sea and Gulf of Alaska. While the program takes full advantage of resource leveraging with other NOAA programs (e.g. FOCI and FATE), and with outside funding sources (e.g. North Pacific Research Board and National Science Foundation), funding for this program must be increased to the full amount in the original funding profile ($6M) to reap all of the intended benefits. External funding currently is used to maintain the four biophysical moorings and process their data because of shortfalls in NOAA funding. Our major external partner, the North Pacific Research Board has notified us that they will stop funding this effort in 2010. In addition, the strong support of the Climate and Ecosystem Goal Teams for continued access to oceanographic and fisheries survey vessels is critical. Our data gathering, and hence efforts to achieve a mechanistic understanding, is hampered by lack of available NOAA ship time. Threatened decreases in the size of the NOAA Pacific fleet will make the shortage worse.

FOCI has been level funded since 1986. For it to play a major role in climate research, adjustments to base are necessary to account for the erosion of program funds by inflation. As with NPCREP, the strong support of the Climate and Ecosystem Goal Teams for continued access to oceanographic and fisheries survey vessels is critical. FATE has also been limited in the number of projects it can support. Increased funding to FATE would allow for more projects to occur simultaneously and would hasten the transformation of understanding and knowledge about individual species and multispecies assemblages into predictive capacity that would enable our assessment scientists to better advise resource managers and our stakeholders on future climate-induced changes on our ecosystems and their living marine resources.

Climate Information Needs

- Fine-scale (both time and space) surface and vertical temperature, salinity, oxygen, nitrate and chlorophyll fluorescence in the Gulf of Alaska and Bering, Chukchi and Beaufort Seas. Sea ice extent and thickness in the Bering, Beaufort, and Chukchi Seas. Sea level and 500 mb pressure maps, output from MM5 winds. Formats geographically indexed and compatible with GIS.
- Downscaled IPCC climate scenarios resolved to drive kilometer and hourly-scale Regional Ocean Circulation Models (ROMS) with ice. Archived runs of ROMS from 1900s to present.

II. Loss of Sea Ice

Description

Bering Sea fisheries account for greater than 40% of the U.S. commercial catch. More than thirty Alaska Native communities depend on subsistence harvests of marine mammals. With increased average water temperatures there has been a loss of sea ice coverage and a northward shift of biological communities (Figure 4). Major food web pathways differ between different regions of the Bering Sea and the loss of sea ice may have different effects on the dominant biota in each region (pollock and other pelagic predators in the southern region, gray whales and other benthic foragers in the northern region). Some commercial fish and shellfish species have shifted outside areas NOAA currently surveys and thus are incompletely monitored, potentially aliasing population assessments. Some marine mammal species depend on the sea ice habitat that is disappearing, and these species are not monitored (Figure 5). At the end of 2007, the NMFS received its first petition to

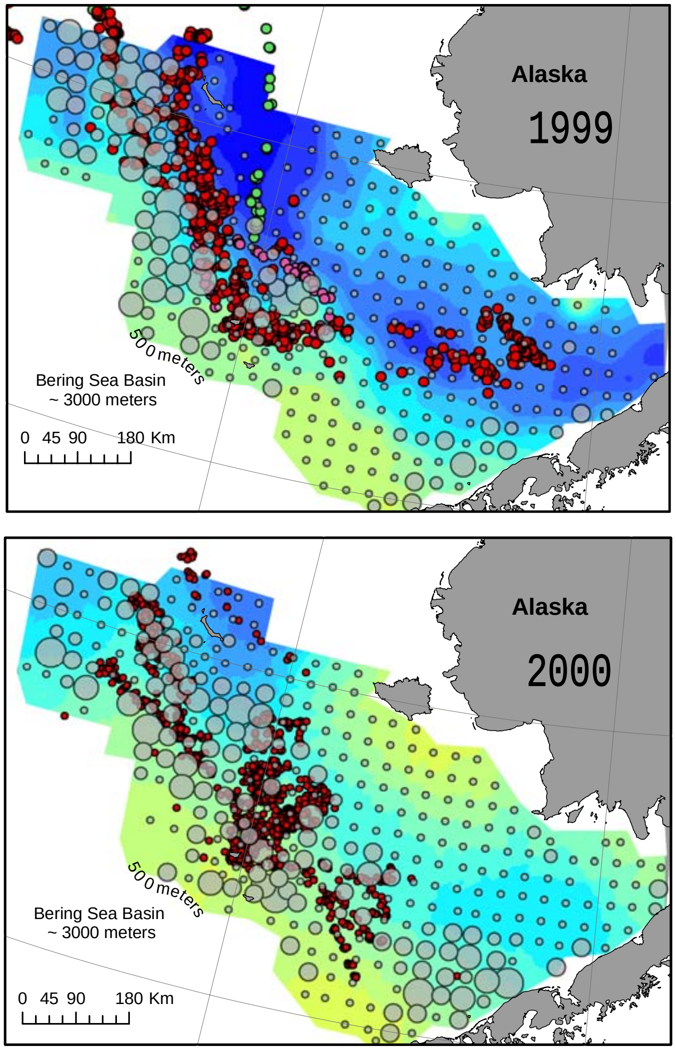

Figure 4. Pollock (gray circles) avoided the extensive cold pool (blue region) in 1999, as did their predators, fur seals (red circles), whereas both species spread out with warmer temperatures in 2000. Temperature range of -1.6 C (deep blue) to +4.0 C (yellow green). Courtesy of J. Sterling, AFSC.

list one of the ice-dependent seal species as threatened or endangered. Increased temperatures and loss of sea ice have co-occurred with recent increases in piscivorous predators such as arrowtooth flounder in the southern Bering region, and an overall decline in benthic productivity in the northern Bering region. New biological communities are forming because species' population centers shift northward at different rates, thus affecting trophic interactions and the recruitment and biomass of renewable resources. Without improved stock assessment capability, fish harvests will be reduced owing to increased uncertainty, resulting in a substantial loss to the U.S. economy (e.g., 10% reduction in pollock harvest is worth $80M) and changes in some marine mammal populations due to the loss of sea ice will not be known.

Current Activities

Current activities are limited. An NPCREP project demonstrated northerly movement of groundfish populations within the main survey area in the southern Bering region (Mueter and Litzow, 2008). Cooperative agreement funds were used in one year to extend the Bering Sea bottom trawl survey to more northern stations as a pilot study, but this effort was not continued due to lack of funding. The AFSC/National Marine Mammal Laboratory conducted aerial surveys of ice seal distribution during spring and tracking of ice dependent seals using satellite tags in 2006 and 2007; these studies depend on National Science Foundation provided helicopter and ship time which may not be available in the future. In the northern Bering region, dramatic declines in sea ice have resulted in a reduction of benthic prey populations, an increase in pelagic fish and a displacement in marine mammal populations. The National Marine Mammal Laboratory was able to conduct one survey in an area that was prime gray whale feeding habitat in 2002, but funds for follow-up investigations have not been available.

Research Needs

- Expand existing surveys in the southeastern Bering Sea (bottom trawl, acoustic-midwater trawl surveys) to cover the current commercial fishery area and initiate routine gray whale (acoustic and visual surveys), ice seal (aerial survey and satellite tagging) and ocean temperature monitoring.
- Conduct the process-based studies required to understand these changes. Assess the impacts of the loss of sea ice in the Bering Sea on vital rates (growth, maturity, and feeding) and movement. Assess whether spatial shifts are creating new biological


M. Cameron, AFSC

Figure 5. Ribbon seal (*Phoca fasciata*) on an ice floe in the eastern Bering Sea. Current research on the distribution and abundance of ice seals is dependent on funding, ships, and aircraft provided by sources outside of NOAA.

communities and altering food webs. Forecast distribution and abundance of managed species and the economic and sociological impacts on the commercial and subsistence fisheries of the Bering Sea.
- Monitor fish, shellfish and marine mammal species in the northern Bering Sea where northward expansion of species is expected.

Resource Needs

Funding is necessary to expand existing surveys in the southeastern Bering Sea to cover the current commercial fishery area and expand whale, seal and ocean temperature monitoring. Additional funding would support the process-based studies required to understand these changes and expand existing surveys to the northern Bering Sea.

Climate Information Needs

- Fine-scale (both time and space) surface and vertical temperature, salinity, oxygen, nitrate and chlorophyll fluorescence in the Gulf of Alaska and Bering, Chukchi and Beaufort Seas. Sea ice extent and thickness in the Bering, Beaufort, and Chukchi Seas. Sea level and 500 mb pressure maps, output from MM5 winds. Formats geographically indexed and compatible with GIS
- Downscaled IPCC climate scenarios resolved to drive kilometer and hourly-scale Regional Ocean Circulation Models (ROMS) with ice. Archived runs of ROMS from 1900s to present.

III. Ocean Acidification

Description

The North Pacific Ocean is a sentinel region for the biological impacts of ocean acidification. It will be one of the first regions affected by decreasing ocean pH because the depth below which the water is understaturated in calcium carbonate (the 'calcium carbonate saturation horizon') is relatively shallow in the North Pacific Ocean (Figure 6). For example, the aragonite (one of two major forms of $CaCO_3$) saturation horizon is at about 200 m depth in the North Pacific Ocean

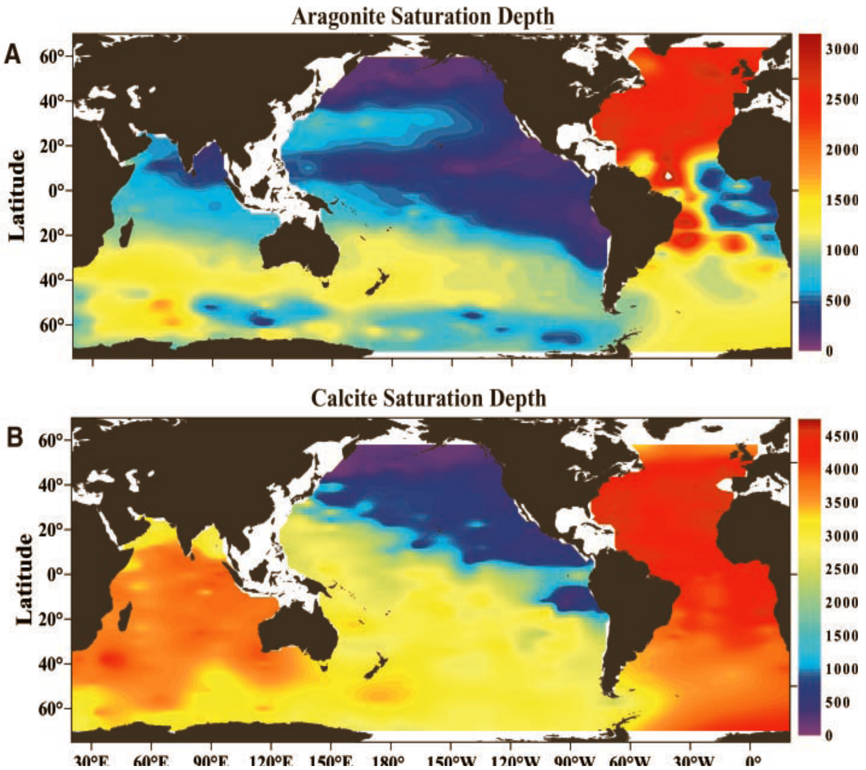

Figure 6. Saturation depths (m) of aragonite (A) and calcite (B) (the two major forms of $CaCO_3$) are much shallower in the North Pacific Ocean than in the North Atlantic Ocean. (Feely et al., 2004)

compared to about 2500 m depth in the North Atlantic Ocean (Feely et al., 2004). In the North Pacific Ocean, the upward migration of the aragonite saturation horizon from pre-industrial times to present has been between 30 and 100 m (Feely et al., 2004). The saturation horizon is projected to reach the surface during this century (Orr et al., 2005). At that point, a wide range of North Pacific species will be exposed to seawater undersaturated with respect to calcium carbonate and may be unable, or have difficulty, forming the carbonate structures needed for their shells or other body components.

Current Activities

Alaska Fisheries Science Center (AFSC) scientists have been conducting pilot ocean acidification research on shellfish since 2006. Their approach has included:

- Identification of shellfish species that may be affected;
- Development of laboratory studies to test hypotheses related to the direct effects of decreased pH and undersaturation of $CaCO_3$ in seawater;
- Identification of response variables that would be appropriate to assess ocean acidification impacts;
- Development of *in situ* process studies to address the magnitude of importance that ocean acidification may have on coastally important shellfish species.

AFSC scientists also have applied ecosystem modeling to forecast how reduced pteropod abundance (pelagic snails) could affect pink salmon abundance in the Gulf of Alaska; pteropods can be important prey for pink salmon.

Research Needs

The Alaska Fisheries Science Center (AFSC), as part of its integrated ecosystem approach to studying living marine resources from the North Pacific Ocean and Bering Sea, has plans for needed ocean acidification research to occur through a four-step progression from understanding species-specific physiological effects to applying this understanding to forecast population and economic consequences:

- Conduct research targeted at understanding species-specific physiological responses to ocean acidification.
- Develop models to forecast the population, community and ecosystem impacts of the physiological responses.
- Develop scenarios to forecast economic consequences of these impacts.
- Collaborate with NOAA's Pacific Marine Environmental Laboratory to monitor ocean pH using AFSC's NOAA and chartered shiptime.

We would focus on understanding effects of ocean acidification on coldwater corals and commercially important fish and shellfish species. Both direct (e.g. reduced survival) and indirect effects (e.g. reduced prey abundance) would be studied.

Focal species would be:

- Commercially important crab species (king crab species)
- Ecologically important prey of commercial fish species (pteropods, euphausiids)
- Coldwater corals
- Commercially important fish species (pollock, cod)

Climate change may affect both ocean pH and temperature, and to the extent practicable both factors would be integrated in our studies. We also would plan to collaborate with other Fishery Science Centers (PIFSC, SWFSC, NWFSC) in the first-affected region (Pacific Ocean).

Resource Needs

Additional funding for the Alaska Fisheries Science Center is needed to support species-specific physiological experiments and population, ecosystem and economic models to forecast population and ecosystem effects and economic consequences. Also, additional funding and ship time are needed by the Pacific Marine Environmental Laboratory for ocean pH measurements that would be critically needed as part of the planned ocean acidification research.

Climate Information Needs

- Surface and vertical ocean pH and carbon species measurements in the Gulf of Alaska and Bering, Chukchi and Beaufort Seas, especially over the continental shelf and slope where fish, shellfish and marine mammal species are concentrated.
- Fine-scale (both time and space) surface and vertical temperature, salinity, oxygen, nitrate and chlorophyll fluorescence in the Gulf of Alaska and Bering, Chukchi and Beaufort Seas. Sea ice extent and thickness in the Bering, Beaufort, and Chukchi Seas. Sea level and 500 mb pressure maps, output from MM5 winds. Formats geographically indexed and compatible with GIS
- Downscaled IPCC climate scenarios resolved to drive kilometer and hourly-scale Regional Ocean Circulation Models (ROMS) with ice and CO_2 chemistry. Archived runs of ROMS from 1900s to present.

Program Integration

The proposed programs are highly integrated and matrixed within NOAA and between NOAA and the regional research community. First, Loss Of Sea Ice (LOSI), NPCREP, FOCI, and Ocean Acidification (OA) are all collaborative programs between NMFS and OAR. FOCI has a 22-year history as a successful matrixed program and the parties have been working together for 4 years in NPCREP. Plans for LOSI and OA have been jointly developed by AFSC and PMEL. These researchers have a strong history of working with other Federal, State, University and NGO researchers in the Bering Sea and the Gulf of Alaska. The AFSC and PMEL just successfully competed an Integrated Ecosystem Research Program proposal with the North Pacific Research Board (NPRB) for a vertically integrated study of the eastern Bering Sea. Included in the new program are scientists from the U.S. Fish and Wildlife Service (USF&WS), University of Alaska, University of Washington, and Oregon State University. The project will collaborate with the National Science Foundation (NSF) sponsored Bering Ecosystem Study (BEST) which has attracted scientists from around the U.S. and Canada. Prior to submission of these proposals, the AFSC, PMEL, NPRB, and NSF sponsored several workshops to begin coordination of climate change and loss of sea ice research activities in the Bering Sea (Bering Sea Interagency Working Group, 2006). Active in the group were the Alaska Ocean Observing System, USF&WS, U.S. Geologic Survey, U.S. Arctic Commission, NPRB, NSF and NOAA.

References

Anderson, P. J., and J. F. Piatt. 1999. Community reorganization in the Gulf of Alaska following ocean climate regime shift. *Mar. Ecol. Prog. Ser.* 189: 117-123.

ACIA. 2004. Impacts of a warming arctic: Arctic Climate Impact Assessment. Cambridge Unversity Press, 139 p.

Bering Sea Interagency Working Group. 2006. Climate change and the Bering Sea ecosystem: An integrated, interagency / multi-institutional approach. AFSC Processed Report 2006-01, 30 p. Alaska Fisheries Science Center, National Marine Fisheries Service, NOAA, 7600 Sand Point Way NE, Seattle WA 98115.

Bering Ecosystem Study (BEST) 2004. BEST Science Plan. Arctic Research Consortium of the United States. Fairbanks, AK 82 p.

Boldt, J. 2006. Ecosystems Considerations for 2007. North Pacific Fisheries Management Council. http://www.afsc.noaa.gov/REFM/docs/2006/EcoChpt.pdf

Ciannelli, L., K. M. Bailey, K. S. Chan, A. Belgrano, and N. C. Stenseth. 2005. Climate changing causing phase transitions of walleye pollock (Theragra chalcogramma) recruitment dynamics. *Proc.R. Soc. Lond. B* 272: 1735-1743.

Connors, M. E., A. B. Hollowed, and E. Brown 2002. Retrospective analysis of Bering Sea bottom trawl surveys: regime shift and ecosystem reorganization. *Prog. Oceanogr.* 55: 209-222.

Feely, R. A., C. L. Sabine, K. Lee, W. Berelson, J. Kleypas, V. J. Fabry, and F. J. Millero. 2004. Impact of anthropogenic CO_2 on the $CaCO_3$ system of the oceans. *Science* 305: 362-366.

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.

Hare, S. R., and N. J. Mantua. 2000. Empirical evidence for North Pacific regime shifts in 1977 and 1989 *Prog. Oceanogr.* 47: 103-145.

Hollowed, A. B., S. R. Hare, and W. S. Wooster. 2001. Pacific Basin climate variability and patterns of Northeast Pacific marine fish production. *Prog. Oceanogr.* 49: 257-282.

Hunt, G. L., Jr., P. J. Stabeno, G. Walters, E. Sinclair, R. D. Brodeur, J. M. Napp, and N. A. Bond. 2002. Climate change and control of the southeastern Bering Sea pelagic ecosystem. *Deep-Sea Res. II*, 49: 5821-5853.

Jurado-Molina, J., and P. Livingston 2002. Climate-forcing effects on trophically linked groundfish populations: Implications for fisheries management. *Can. J. Fish. Aquat. Sci.* 59: 1941-1951.

Kendall, A. W., Jr., J. D. Schumacher, and S. Kim 1996. Walleye pollock recruitment in Shelikof Strait: applied fisheries oceanography. *Fish. Oceanogr.* 5(Suppl. 1): 4-18.

Lanksbury, J. A., J. T. Duffy-Anderson, K. L. Mier, M. S. Busby and P. J. Stabeno 2007. Distribution and transport patterns of northern rock sole, Lepidopsetta polyxstra, larvae in the southeastern Bering Sea. *Prog. Oceanogr.* 72: 39–62.

Litzow, M. A., K. M. Bailey, F. G. Prahl, and R. A. Heintz. 2006. Climate regime shifts and reorganization of fish communities: the essential fatty acid limitation hypothesis. *Mar. Ecol. Prog. Ser.* 315: 1-11.

Litzow, M. A. and L. Ciannelli. 2007. Oscillating trophic control induces community reorganization in a marine ecosystem. *Ecol. Letters* 10: 1124-1134..

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

Mueter, F. J., C. Ladd, M. C. Palmer, and B. L. Norcross. 2006. Bottom-up and top-down controls of walleye Pollock (*Theragra chalcogramma*) on the eastern Bering Sea shelf. *Prog. Oceanogr.* 68: 152-183.

Mueter F. J., and M. A. Litzow. 2008. Sea ice retreat alters the biogeography of the Bering Sea continental shelf. *Ecological Applications*. 18(2): 309-320.

Orr, J. C., V. J. Fabry, O. Aumont, L. Bopp, S. C. Doney, R. A. Feely, A. Gnanadesikan, N. Gruber, A. Ishida, F. Joss, R. M. Key, K. Lindsay, E. Maier-Reimer, R. Matear, P. Monfray,

A. Mouchet, R. G. Najjar, G. Plattner, K. B. Rodgers, C. L. Sabine, J. L. Sarmiento, R. Schlitzer, R. D. Slater, I. J. Totterdell, M. 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.

Stabeno, P. J., and J. E. Overland. 2001. Bering Sea shifts toward an earlier spring transition. *EOS. Trans. AGU* 29: 317, 321.

Wilderbuer, T. K., A. B. Hollowed, W. J. Ingraham, Jr., P. D. Spencer, M. E. Conners, N. A. Bond, and G. E. Walters. 2002. Flatfish recruitment response to decadal climatic variability and ocean conditions in the eastern Bering Sea. *Prog. Oceanogr.* 55: 235-247.

Pacific Island Ecosystem Complex

Authors:
Ellen Smith
(Joint Institute for Marine and Atmospheric Research, Univ. of Hawaii)
Jason Baker
(Pacific Islands Fisheries Science Center)

Introduction

The Pacific Islands region lies largely within the subtropical gyres of the North and South Pacific Oceans. These gyres are characterized by warm, vertically stratified, low nutrient and low surface chlorophyll waters. The resources of interest in the region can be grouped as either highly migratory species (HMS) or as insular and island associated species. The HMS species are treated in another section of this report so we focus on the insular species in this section. Within the insular species, management interests include the diverse coral reef ecosystem and marine mammals and turtles, including protected species such as green sea turtles and monk seals, which use the beaches for nesting or pupping and forage around the islands. Deepwater corals and deepwater snappers are also important components of the insular complex.

Climate Induced Ecosystem Concerns

Prioritization of the climate related ecosystem concerns for the Pacific Islands is difficult because the region is vast and the biogeochemical conditions that exist in one region do not necessarily exist in another. In addition, climate related concerns may have different outcomes in different island regions of the Pacific. Rising sea level, for example, will likely affect the low lying atolls on the North Western Hawaiian Islands significantly more than the high islands in the Commonwealth of the Northern Marianas Islands. Links between climate events and insular species have been investigated in the Hawaiian Archipelago (Antonelis et al., 2003; Baker et al., 2006; Polovina et al., 1994). The highest priority climate related ecosystem concerns in the Pacific Islands region are:

I. Coral bleaching
II. Sea level rise
III. Ocean acidification
IV. Changes in ENSO and ocean circulation patterns

I. Coral Bleaching

Description

Coral reef ecosystems are composed of a highly diverse assemblage of hundreds of thousands of plant and animal species, all existing in a very dynamic interaction with each other and the physical environment. These ecosystems are distributed throughout the tropical and subtropical surface waters of the Pacific Ocean between approximately 25°N and 25°S and coincide with water temperatures between 18°C and 30°C and salinities from 32-40 psu (Hoegh-Guldberg, 1999). The increase in water temperatures associated with global warming (1-2°C per century) and regionally specific ENSO events are leading to increased incidences of coral bleaching in the Pacific Islands region. Coral bleaching and subsequent mortality can lead to habitat phase shifts where corals are replaced by algal functional groups. Although recent research has documented algal-dominated areas to occur naturally on many healthy Pacific reef systems (Vroom et al., 2006), algal overgrowth of coral dominated areas as the result of anthropogenic climate change are indicative of decreased ecosystem health. This phase shift may result in decreased calcium carbonate accumulation, and impact the reef fauna that depend on the structural complexity provided by corals. The persistently increasing temperatures associated with global warming are likely to increase the frequency and magnitude of coral bleaching events in the Pacific Islands Ecosystem Complex.

Current Activities

During the 2007 U. S. Coral Reef Task Force meeting a new climate change working group was formed and an action plan for the International Year of the Reef 2008 involving government and non-government partners in conservation was endorsed. The new climate change working group is charged with developing best practices to help local resource managers minimize the impact of climate-induced stresses like coral bleaching, while better educating the public about the impacts of climate change on the health and survival of reef resources. Components of the decision called for developing bleaching response plans for each U.S. state and territory with reefs, and assessing what expertise and resources federal agencies have to mitigate risk and damage. The Task Force also hosted a special session on the health of coral reef ecosystems in a changing climate, drawing from the regional and international expertise to highlight common challenges and management needs. The Task Force further called on members and partners to reduce greenhouse gas emissions and affirmed the role that regional networks of marine protected areas can play in protecting ecological connectivity among islands in the face of potential future losses that may result due to climate change. The creation of the climate change group is considered a major new step for the Task Force, but one that builds on several past resolutions and the 2006 release of The Reef Manager’s Guide to Coral Bleaching (Marshall and Schuttenberg, 2006). The Reef Manager’s Guide provides information on the causes and consequences of coral bleaching, and helps managers understand and plan for bleaching events.

Currently the Coral Reef Ecosystem Division (CRED) of NMFS Pacific Islands Fisheries Science Center (PIFSC) has Coral Reef Early Warning System (CREWS) buoys deployed throughout the Pacific Islands Ecosystem Complex which provide high resolution telemetered data and long-term monitoring of sea surface temperature (SST), barometric pressure, wind speed and direction, salinity, UV-B, and PAR. Extended periods of low winds, increased temperatures and downwelling light signatures are indicative of potential bleaching events.

Research Needs

- Share strategies and tools that predict where coral bleaching will occur.
- Measure coral reef resilience.
- Assess the socioeconomic impacts of damage related to climate change.
- Advance our understanding of the links between bleaching events and the impacts to the reef fish community.
- Use coupled ocean-climate models to better understand the spatial and temporal patterns of ocean warming.
- Enhance and integrate *in situ* and satellite-based coral bleaching and alert systems.

II. Sea Level Rise

Description

Rising sea level is a concern for terrestrial habitats and the biological community that depends on them, as well as for shallow water coral reef communities. Depending on the rate of the sea level increase, reef-building corals may be unable to accrete at a rate that maintains close enough proximity to the surface to sustain the nutritional needs of the ecosystem. Rising sea levels will overwhelm coastlines around the Pacific affecting human life and increasing the amount of both sediment and nutrient pollutants that reach the ocean. Nesting sites for marine turtles and other species will be impacted due to the alteration of shore lines and other low-lying areas. The reduction in nesting and pupping beaches in the Northwestern Hawaiian Islands for the Hawaiian Monk Seal and Green Sea turtle are of primary concern. Increased sea level combined with less effective barrier reefs will allow greater energy to reach the shoreline in the forms of waves and currents, thereby altering coastal ecosystems. Many of the low-lying atolls in the Pacific Islands Ecosystem Complex are forecasted to be completely submerged by rising sea-levels and will have to be evacuated.

Terrestrial habitats in the Northwestern Hawaiian Islands (NWHI) consist largely of low-lying oceanic sand islands (cays) and atolls which support a spectacular biological community, including numerous terrestrial species which are only found on these islands (Conant et al., 1984). The NWHI are also important for large marine vertebrates including sea birds, green sea turtles and Hawaiian monk seals, all of which feed at sea but require terrestrial habitat with few or no predators to either nest or raise offspring. The Hawaiian monk seal, listed as endangered under the U.S. Endangered Species Act (1973), has a population of less than 1300 individuals, primarily in the NWHI (Baker and Johanos, 2004; Antonelis et al., 2006; Carretta et al., 2006). Female seals typically give birth on sandy beaches adjacent to shallow waters, which offer neonates access to the sea while providing some protection from large waves and the approach of predatory sharks (Westlake and Gilmartin, 1990). Hawaiian green sea turtles, listed as threatened under the Endangered Species Act, range over the entire Hawaiian archipelago, but over 90% of breeding females nest at one NWHI atoll, French Frigate Shoals, where their number has been increasing for the past 30 yr (Balazs and Chaloupka, 2004). The NWHI are also habitat for 14 million seabirds of 18 species (Harrison, 1990). The islands are particularly important nesting habitat for Laysan and black-footed albatross, the sooty, or Tristram's, storm petrel, and Bonin petrels (Fefer et al., 1984; Harrison, 1990).

Despite the NWHI's high conservation value, the impacts of sea-level rise on terrestrial habitats in the region have been largely overlooked until recently. The low-lying land areas of the NWHI are highly vulnerable to sand erosion due to storms and sea-level rise. Sea-level rise reduces cays by passive flooding, active coastal erosion, and in concert with seasonal high swell. As a result, these important littoral and coastal ecologies are at risk. Demonstrating this, islands at French Frigate Shoals have been greatly reduced in size during roughly the past 40 years for reasons not well understood, as this occurred during a period when sea level rose relatively little (Antonelis et al., 2006). Another example of this is the effective disappearance of Whaleskate Island, which had been important habitat for turtles and seals (Fig. 1).

Figure 1. Whaleskate Island at French Frigate Shoals, NWHI. Once an important nesting island for Hawaiian green sea turtles and a primary pupping site for endangered Hawaiian monk seals, pictured from the air in 1963 (left) and in 2002 (right).

Current Activities

Concerns about sea level rise in the NWHI motivated a study to project what might happen as global sea level increases in the future. Baker et al. (2006) produced the first NWHI topographic maps in three locations (Lisianski Island, Pearl and Hermes Reef, and French Frigate Shoals). They then used passive flooding scenarios to estimate the area that would be lost if islands maintained their current topography and the sea were to rise by various amounts within the range predicted by the 2001 Intergovernmental Panel on Climate Change (IPCC). The projected effects of sea level rise on surface area varied considerably among the islands examined (Fig. 2). For example, Lisianski Island is projected to be the least affected of the islands surveyed, losing only 5% of its area with an 88 cm rise in sea level. In contrast, the islets at French Frigate Shoals and Pearl and Hermes Reef are projected to lose between 15 and 65% of their area with a 48 cm sea level rise.

The uncertainty of predictions increases over time, but the expectation is that sea level will continue to rise beyond 2100 (Church et al., 2001). Moreover, recent evidence suggests that sea level may rise more rapidly than previous models have predicted, due in part to an accelerated rate of ice loss from the Greenland Ice Sheet (Rignot and Kanagaratnam, 2006).

Research Needs

- High resolution mapping of all islands (preferably using Light Detection and Ranging, LIDAR) including characterization of the extent and thickness of erodable substrate is required.
- Modeling of shoreline evolution under higher sea level with elevation, bathymetric, hydrodynamic and geologic substrate data inputs, to indicate the effects of sea-level rise on sediment transport and resulting evolution of sandy cays and impacts on terrestrial habitats.
- Development of strategies for mitigating hazards posed by sea-level rise using, for example, beach nourishment (Hanson et al., 2002).

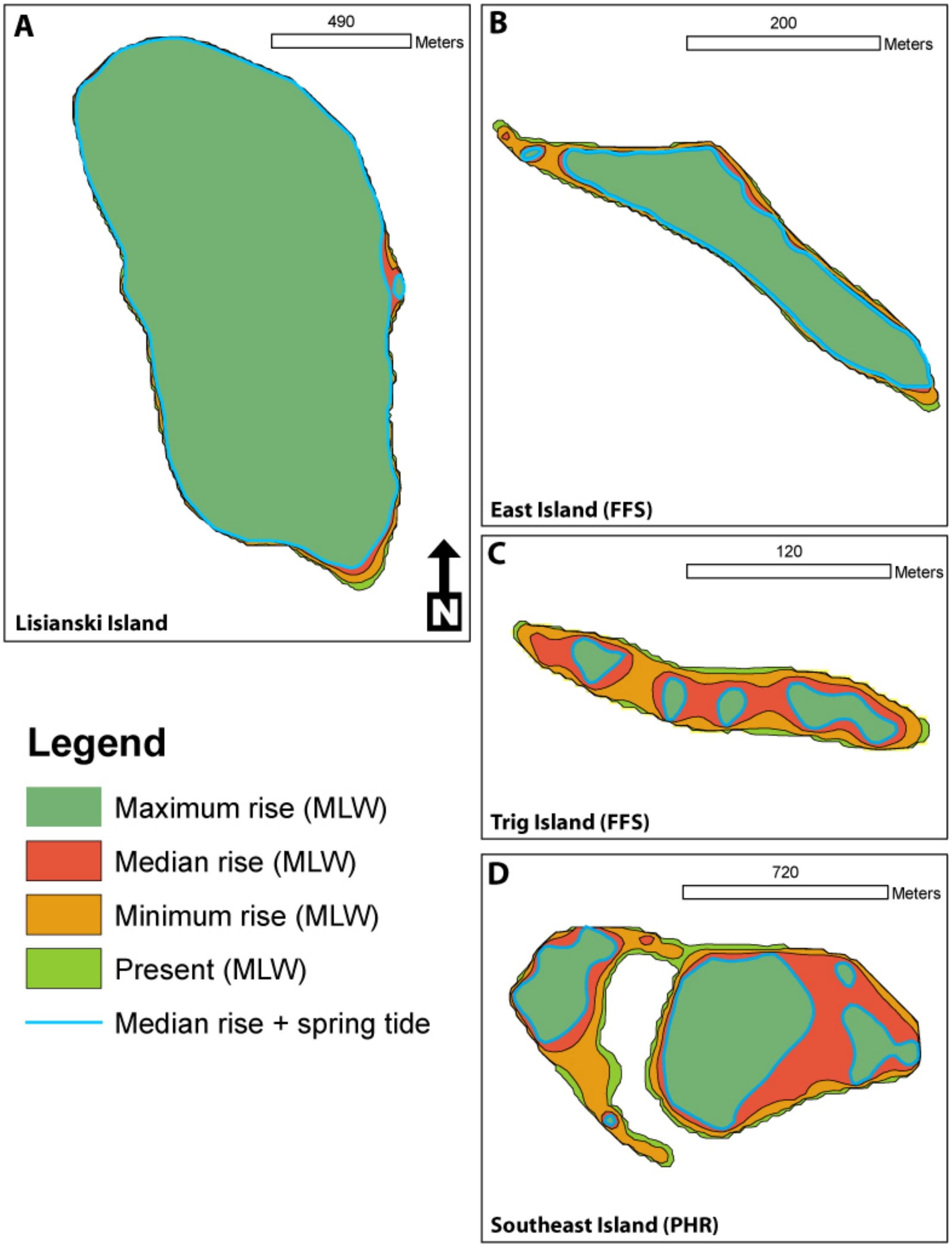

Figure 2. Current and projected maps of four Northwestern Hawaiian Islands at mean low water (MLW) with minimum (9 cm), median (48 cm) and maximum (88 cm) predicted sea-level rise by 2100. The median scenario at spring tide is also shown. A) Lisianski Island; B) East Island, French Frigate Shoals; C) Trig Island, French Frigate Shoals; D) Southeast Island, Pearl and Hermes Reef. (Baker et al., 2006)

III. Ocean Acidification

Description

A coral reef represents the net accumulation of carbonate minerals produced by reef-building corals and other calcifying organisms. The living component of the reef is the uppermost layer of the limestone foundation formed by calcifying organisms dating back to millions of years. This living layer of the coral reef offers a highly 3-dimensional environment to all of the living organisms that call the reef ecosystem home. Coral reefs are susceptible to ocean acidification because reef calcification depends on the saturation state of carbonate minerals in surface waters which decrease with increasing levels of carbon dioxide and the concomitant decrease in pH. By the middle of this century, an increased concentration of CO_2 will decrease the saturation state with respect to carbonate minerals in the tropics by 30 percent and biogenic carbonate precipitation by 14 to 30 percent (Kleypas et al., 1999).

Current Activities

Approximately 150 water samples have been collected for sea water chemistry analysis from approximately 25 sites around the American Samoa region in two separate years as part of ongoing CRED Reef Assessment and Monitoring Program biennial cruises. For increased temporal resolution of carbonate chemistry, research and development is continuing on sensor systems for *in situ* metabolic monitoring of the carbonate system in coral reef environments.

Research Needs

To date, efforts to examine the response of marine calcifying reef organisms to future changes in carbonate chemistry have been mostly limited to controlled laboratory experiments and models, with little research examining the impacts of ocean acidification on the community structure of coral reef ecosystems in the real ocean.

- Understanding the biological responses to ocean acidification is critical for predicting and conserving reef ecosystem health in the face of climate change. Biological calcification processes and seawater carbonate chemistry need to be assessed and monitored at strategic near-shore coral reef sites in the U.S.-affiliated Pacific Islands, thereby providing an improved understanding of ecosystem level responses to ocean acidification.
- Development and implementation of methodologies to describe the spatial structure of the carbonate system from a variety of reef zones and habitat types is needed to insure proper utilization of the metabolic monitoring stations currently being developed by Feely, Sabine and Wanninkhof (PMEL/AMOL) to gauge the system response to increases in CO_2.
- Coral cores need to be collected to examine long-term changes in biological response to increases in CO_2. Development and testing of promising new technologies, specifically the use of underwater ultrasound (and other acoustic tools), to examine recent calcification rate changes of a broad spectrum of the coral community would allow an unprecedented ability to monitor ecosystem level responses to ocean acidification.
- A program to collect long-term records of carbon cycle parameters and analyze the impacts of changing carbonate equilibrium on coral reef ecosystems needs to be developed, and historical records of coral reef environmental variability using paleo-climatic records of SST and other parameters from coral skeletons needs to be reconstructed.

IV. Changes in ENSO and Ocean Circulation Patterns

Description

El Niño-Southern Oscillation (ENSO), resulting from the large-scale global coupling of atmospheric and oceanic circulation, is an inter-annual climatic phenomenon (approximately 3 – 8 years) that creates significant temperature fluctuations in the tropical surface waters of the Pacific Ocean. ENSO events can have a significant impact on coral reef ecosystems due to changing surface winds, storm events, ocean currents, water temperatures, nutrient availability, storm frequency and magnitude, etc. ENSO is a naturally occurring phenomenon, however, there is uncertainty regarding how global warming and the associated climate changes will impact the frequency, magnitude and importantly the duration of this cycle and how that will in turn affect coral reef ecosystems. Changes to established ocean circulation patterns can have significant effects on biological connectivity, distribution of species, biological productivity, and marine debris issues. Changes in storm events can impact corals directly from wave damage or more indirectly from runoff and sediment deposition.

Current Activities

The Tropical Atmosphere Ocean/Triangle Trans-Ocean Buoy Network array consists of approximately 70 moored buoys all over the Pacific basin designed for the study of year-to-year climate variations related to ENSO. This array is geared towards improved detection, understanding and prediction of El Niño and La Niña. Correlations between physical and ecological parameters during the fluctuating ENSO forced conditions are starting to be studied more carefully as time series data sets are continuing to grow, covering a temporal range that encompasses many of these varying phases.

Research Needs

- Use output from coupled ocean-climate models (IPCC models) to examine how ENSO dynamics might change in the future and where these changes might have the greatest impacts on coral reefs.
- Develop models that downscale the IPCC model output that have specific relevance to coral reefs.

Resource and Climate Information Needs

Due to the similarities of these needs for all Pacific Island climate induced ecosystem concerns, these needs are just provided here.

Resource Needs

For coral reef ecosystems research on impacts from climate change needs funds to maintain and expand long term field monitoring programs. Further, support is required to develop models of bleaching, disease, and coral growth driven from output from IPCC climate models. For NWHI habitat loss from sea level rise, funds to conduct aircraft-based LIDAR surveys and create high resolution maps of islands (and nearshore shallow bathymetry) are needed to characterize, forecast and mitigate sea level rise effects in the Northwestern Hawaiian Islands. Having these data would also be of great use to the co-trustee agencies (NOAA, USFWS, State of Hawaii) charged with managing the new NWHI Marine National Monument.

Climate Information Needs

- Improved spatial and temporal estimates for the Pacific of future changes in key physical and chemical parameters, including temperature, ocean pH, sea level rise, storm intensity, and ENSO dynamics.
- Better tools (models) that permit downscaling from basin-scale IPCC output to islands and atolls.

References

Antonelis, G. A., J. D. Baker, and J. J. Polovina. 2003. Improved body condition of weaned Hawaiian monk seal pups associated with El Nino events: potential benefits to an endangered species. *Marine Mammal Science* 19(3): 590-598.

Antonelis, G. A., J. D. Baker, T. C. Johanos, R. C. Braun, and A. L. Harting. 2006. Hawaiian monk seal (*Monachus schauinslandi*): status and conservation issues. *Atoll Res. Bull.* 543: 75-101.

Baker, J. D. and T. C. Johanos. 2004. Abundance of the Hawaiian monk seal in the main Hawaiian Islands. *Biological Conservation* 116(1): 103-110.

Baker, J. D., C. L. Littnan, and D. W. Johnston. 2006. Potential effects of sea level rise on the terrestrial habitats of endangered and endemic megafauna in the Northwestern Hawaiian Islands. *Endangered Species Res.* 2: 21-30.

Balazs, G. H., and M. Chaloupka. 2004. Thirty-year recovery trend in the once depleted Hawaiian green sea turtle stock. *Biol. Conserv.* 117: 491-498.

Carretta, J. V., K. A. Forney, M. M. Muto, J. Barlow, J. Baker, B. Hanson, and M. Lowry. 2006. U.S. Pacific Marine Mammal Stock Assessments: 2005. NOAA-TM-NMFS-SWFSC-388.

Church, J. A., J. M. Gregory, P. Huybrechts, M. Kuhn, K. Lambeck, M. T. Nhuan, D. Qin, and P. L. Woodworth. 2001. Changes in Sea Level in Climate Change 2001: The Scientific Basis. In: Houghton J. T., Y. Ding, D. J. Griggs, M. Noguer, P. van der Linden, X. Dai, K. Maskell, and C. I. Johnson (eds) Contribution of Working Group I to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press Cambridge, p 641-693.

Conant, S., C. C. Christensen, P. Conant, W. C. Gange, and M. L. Goff. 1984. The unique terrestrial biota of the Northwestern Hawaiian Islands. In: Grigg, RW and Tanoue, KY (eds) Proceedings of the second symposium on resource investigations in the northwestern Hawaiian Islands. Volume 1 Sea Grant Miscellaneous Report UNIHI-SEAGRANT-MR-84-01, Honolulu p. 77-94.

Fefer, S. I., C. S. Harrison, M. B. Naughton, and R. J. Shallenberger. 1984. Synopsis of results of recent seabird research conducted in the Northwestern Hawaiian Islands. In: Grigg, RW and Tanoue KY (eds) Proceedings of the second symposium on resource investigations in the northwestern Hawaiian Islands, Volume 1. Sea Grant Miscellaneous Report UNIHI-SEAGRANT-MR-84-01, Honolulu p. 9-76.

Hanson, H., A. Brampton, M. Capobianco, H. H. Dette, L. Hamm, C. Laustrup, A. Lechuga, and R. Spanhoff. 2002. Beach nourishment projects, practices, and objectives - a European overview. *Coastal Engineering* 47: 81– 111.

Harrison, C. S. 1990. Seabirds of Hawaii: Natural history and conservation. Cornell University Press, Ithaca.

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

Kleypas, J. A., R. W. Buddemeier, D. Archer, J. Gattuso, C. Langdon, and B. N. Opdyke. 1999. Geochemical Consequences of Increased Atmospheric Carbon Dioxide on Coral Reefs. *Science* 284: 118-120.

Marshall, P. A., and H. Z. Schuttenberg. 2006. A Reef Manager's Guide to Coral Bleaching. Great Barrier Reef Marine Park Authority, Australia (ISBN 1-876945-40-0).

Polovina, J. J., G. T. Mitchum, N. E. Graham, M. P. Craig, E. E. Demartini, and E. N. Flint. 1994. Physical and biological consequences of a climate event in the central North Pacific. *Fish. Oceanogr.* 3(1), p. 15-21.

Rignot, E., and P. Kanagaratnam. 2006. Changes in the velocity structure of the Greenland Ice Sheet. *Science* 311: 986-990.

Vroom, P. S., K. N. Page, J. C. Kenyon, and R. E. Brainard. 2006. Algae-Dominated Reefs. *American Scientist* 94: 430-437.

Westlake, R. L., and W. G. Gilmartin. 1990. Hawaiian monk seal pupping location in the Northwestern Hawaiian Islands. *Pac. Sci.* 44: 366-384.

Eastern Tropical Pacific

Authors:
Lisa T. Ballance, Paul Fiedler, and George Watters
(Southwest Fisheries Science Center)

Introduction

The eastern tropical Pacific (ETP) is comprised of approximately 21 million km^2 of ocean between the U.S.-Mexico border, Hawaii, and Peru, and includes a number of oceanographically distinct regions, including the Equatorial Cold Tongue, and the eastern Pacific Warm Pool (between Central America and 120º W, and between 25º N and 5º N, Figure 1). The predominant variability in the ecosystem, both physical and biological, appears to be associated with El Niño-Southern Oscillation events (ENSO; Ballance et al., 2002; Fiedler, 2002; Fiedler and Philbrick, 2002; Gerrodette and Forcada, 2002; Pitman et al., 2002; Reilly et al., 2002a, b). Underlying this ENSO-scale variability are longer-period physical changes, often labeled “climate shifts”. These have been detected throughout the north Pacific, including the ETP.

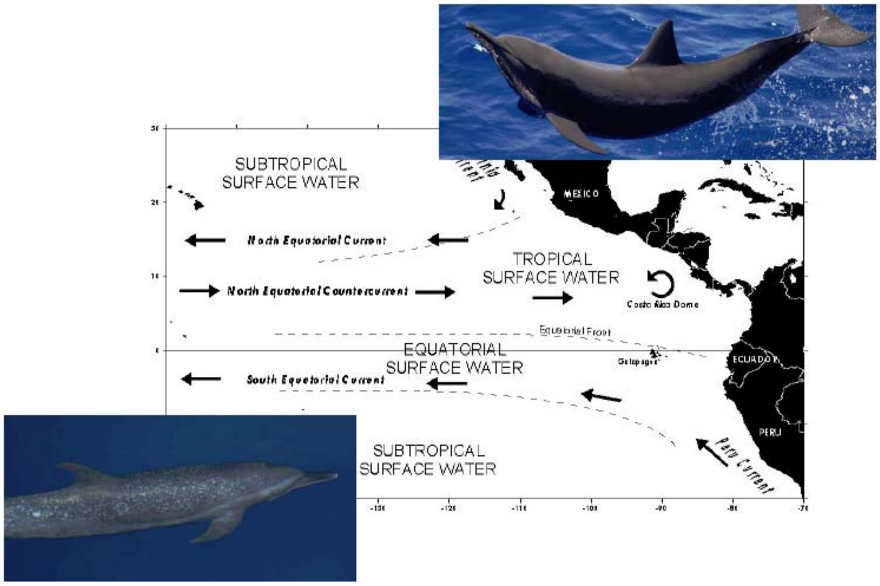

Figure 1. Oceanographic depiction of the eastern tropical Pacific (modified from Wyrtki) and eastern spinner (upper right) and pantropical spotted (lower left) dolphins, two of the stocks depleted through incidental mortality from the yellowfin tuna purse seine fishery.

NOAA Fisheries has been conducting research in this ecosystem since the late 1970s because incidental mortality of northeastern offshore spotted and eastern spinner dolphins due to the yellowfin tuna purse seine fishery resulted in these stocks being designated as “depleted” under the Marine Mammal Protection Act. Despite changes in fishing practices in the early 1990s which reduced observed dolphin mortality to very low levels, it is uncertain whether these stocks are recovering (e.g., Wade et al., 2007; Figure 2). Scientists at the Southwest Fisheries Science Center (SWFSC) have been mandated by Congress under the International Dolphin Conservation Program Act (IDCPA) to conduct research to try to understand the reasons for this lack of recovery.

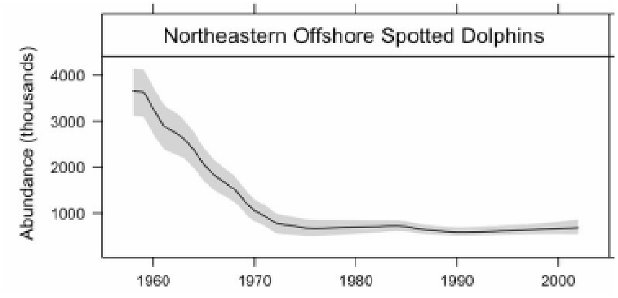

Figure 2. Model-averaged estimated population trajectories for depleted spotted dolphin stocks, 1958 – 2002. (Wade et al., 2007)

Climate Induced Ecosystem Concerns

While there are other climate induced ecosystem concerns in the ETP (e.g. ocean acidification), the highest priorities for NOAA Fisheries are focused on ecosystem concerns as they relate to the lack of recovery of depleted dolphin stocks. Within this framework, the major climate induced ecosystem concerns in order of importance are:

I. The biological effects of ENSO cycles
II. The biological effects of climate shifts, particularly the late 1970s climate shift

I. The biological effects of ENSO cycles

Description

The dominant variation in the ecosystem appears to occur at a two to seven-year periodicity, corresponding to ENSO-scale variation. This variation is evident in both physical (Figure 3) and biological components (reviewed in Fiedler 2002), but the specific relationships between many of the ecosystem components remain largely unquantified. Additionally, there is an indication that El Niño events may be occurring at more frequent intervals or with greater intensity (Miller and Cayan 1994, Stephens et al. 2001). The need to understand specific effects of these cycles on dolphins, and their prey, predators, competitors, and commensals, is great.

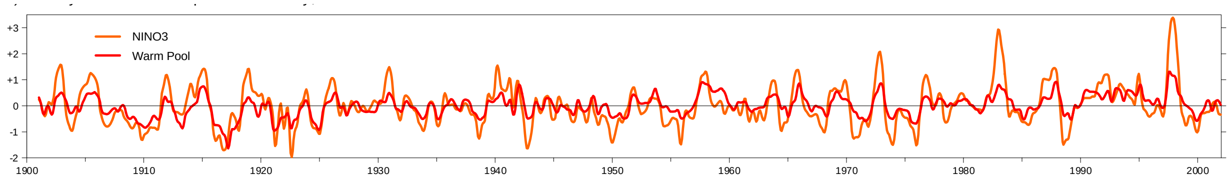

Figure 3. Monthly sea surface temperature anomalies for the equatorial region and Eastern Pacific Warm Pool, 1900-2000. (Fiedler, 2002.)

Current Activities

Current research has focused on a multi-year cetacean and ecosystem assessment survey (Figure 4). A series of research vessel cruises began in the 1970's and are repeated periodically. A five-year series was conducted during 1986-1990, a three-year series was completed from 1998 through 2000, two cruises were conducted in 2003 and 2006; and future monitoring cruises are planned at three year intervals. These surveys utilize two vessels, NOAA ships *David Starr Jordan* and *McArthur II*. Each survey covers approximately 100,000 linear km of trackline.

The surveys use a multidisciplinary approach. Data used to support estimates of stock abundance are collected using state of the art line-transect methods and wide-format photographs of dolphin schools taken from a helicopter or fixed-wing aircraft. Research on cetacean biology provides additional critical information for stock assessment. This includes analysis of skin biopsy samples collected with biopsy darts, acoustic recordings, and lateral photographs to provide information on population structure, use of biopsy samples and aerial photographs to investigate pregnancy rates and demographic composition of schools, and studies to determine how dolphin behavior influences ship-based detection. Ecosystem assessment provides a context in which to place abundance and assessment results and is a critical means of separating fishery- from non-fishery effects on dolphin abundance. Cetacean habitat is characterized through collection of physical and biological oceanographic data, cetacean prey through collection of mid trophic-level fishes and invertebrates, and cetacean predators, competitors, and commensals through studies of other apex predators in the system. These data form the basis for investigations into the effects of ENSO cycles on the ecosystem.

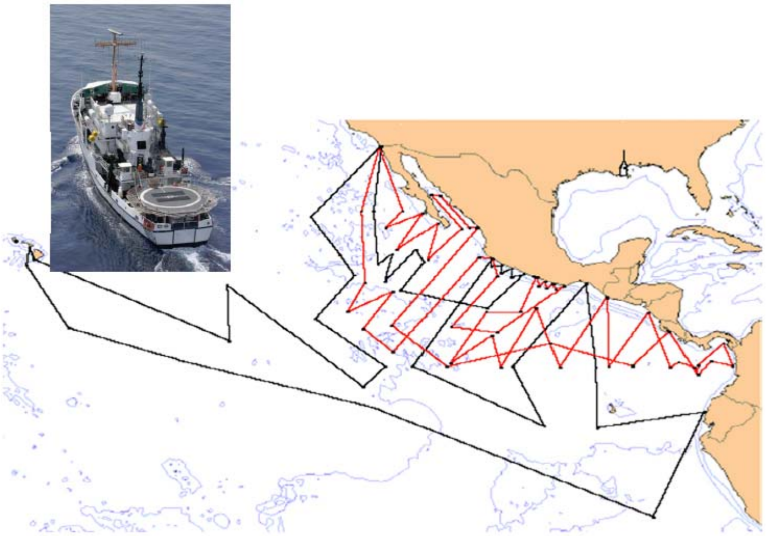

Figure 4. Survey effort in the eastern tropical Pacific, 2006.

Research Needs

- Analyze existing ecosystem data to clarify species-habitat relationships, to identify links (direct and indirect) between trophic levels, and to quantify effects of ENSO-scale variation on the ecosystem.
- Develop ecosystem models to investigate ecosystem structure, function, and responses to ENSO variability (and longer-period climate change).

Resource Needs

Resources needed for these activities primarily consist of additional technicians and post-doctoral level investigators for sample processing and data analysis. Continuation of monitoring activities and undertaking process-oriented research cruises are also important activities and have the added resource need of research vessel days at sea. Monitoring cruises, conducted at least once every three years, will allow documentation of long-term environmental and ecosystem changes and are crucial for understanding long-term population changes. Process research cruises will be valuable to test hypotheses developed as a result of the other investigations.

Climate Information Needs

U. S. and international agencies maintain databases of ETP climate variables including temperature, winds, and precipitation. We will rely on continued archival of oceanographic data from ships and buoys, development of data-assimilation models to cover gaps in observational data, and continued funding and renewal of satellite temperature, wind, and ocean color programs to ensure continuous time series of physical and biological variables.

II. The biological effects of climate shifts, particularly the late 1970s climate shift

Description

One hypothesis put forward to explain the lack of recovery of ETP dolphin stocks to pre-exploitation levels focuses on regime shifts as a cause. Specifically, a climate-induced shift may have altered the ecosystem so as to prevent recovery of depleted dolphin stocks to pre-exploitation levels (Figure 5). Biological responses to the 1976-1977 climate shift have been well documented in many areas of the North Pacific (Venrick et al., 1987; McGowan et al., 1998; Hare and Mantua, 2000; Napp et al., 2002). In the ETP, temporal and spatial scales of climate-ocean coupling differ from those in other parts of the Pacific; hence the biological response to climate shifts is also likely to differ. While biological data that represent the ecosystem prior to 1976 are rare, a few historical datasets offer the opportunity to compare patterns pre- and post-shift in order to obtain insight into climate impacts on the ecosystem.

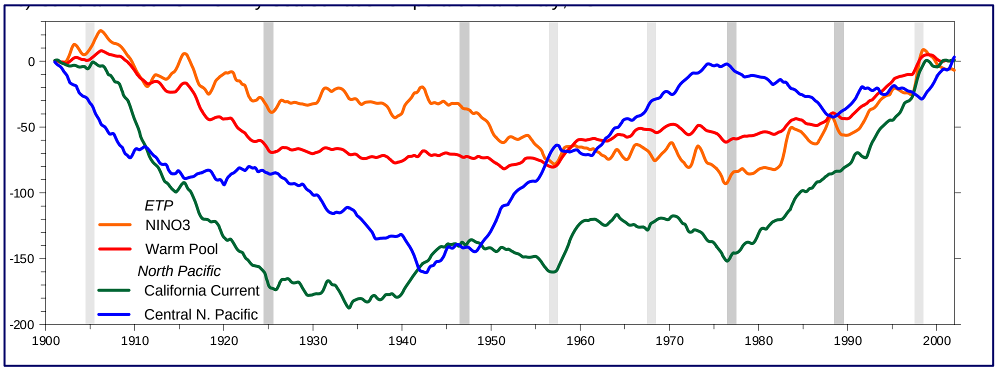

Figure 5. Cumulative sums of monthly sea surface temperature anomalies for four regions in the Pacific. Gray bars identify years in which climate shifts have been detected. The late 1970s shift is evident in the four regions shown in the figure, including the "Warm Pool" which encompasses the eastern tropical Pacific between Central America and 120ºW, and between 25ºN and 5ºN. (Fiedler, 2002.)

Current Activities

There is little current activity focused on these types of investigations due to lack of resources.

Research Needs

- Compare distribution and abundance of zooplankton and micronekton from net samples collected in the late 1960s with samples collected in the late 1980s and 1990s.

  Data available to address this question span the years 1967-1968 (EASTROPAC expeditions) and 1986-2006. During these expeditions, two types of net sampling were used: oblique tows, providing an index of zooplankton abundance and distribution in the upper 200 m of the water column; and horizontal, surface tows, providing an index of zooplankton abundance and distribution at the surface.

- Compare stable isotope signatures from marine turtle, seabird, and cetacean museum specimens with specimens collected more recently to investigate potential diet shifts

Stable isotope analysis has become a common tool to answer questions about the trophic ecology of a variety of marine vertebrates, including cetaceans (Ruiz-Cooley et al., 2004), pinnipeds (Kurle and Worthy, 2002), seabirds (Hobson, 1993), marine turtles (Godley et al., 1997), sharks (Estrada et al., 2003) and bony fishes (Thomas and Cahoon, 1993). These inferences are possible because the isotope compositions of a consumer's body tissues are ultimately derived from those in its diet (DeNiro and Epstein, 1978; 1981; Miniwaga and Wada, 1984; Michener and Schell, 1994). By providing information on nutrients assimilated over extended periods, this technique is much less subject to temporal bias that may result from the 'snapshot' that comes from conventional diet analyses (Peterson and Fry, 1987; Hobson et al., 1996).

- Compare tissue samples from dolphins killed in the purse-seine fishery pre- and post-regime shift to investigate potential changes in demographic parameters

Biological samples collected from dolphins incidentally killed in the fishery from 1968 through 1994 have provided material to estimate birth rates and other parameters that are used to describe life history characteristics (e.g. average age at weaning and at attainment of sexual maturity, breeding season, calving interval, adult length, longevity). Most studies conducted to date using these samples have focused on producing stock-specific estimates of vital rates, while few studies have considered spatial/temporal variability in estimates. Analysis of these samples can provide insight into spatial/temporal variability in these life history characteristics coincident with the 1976-1977 climate shift.

Resource Needs

Resources needed for these activities primarily consist of additional technicians and post-doctoral level investigators for sample processing and data analysis.

Climate Information Needs

U. S. and international agencies maintain databases of ETP climate variables including temperature, winds, and precipitation. We will rely on continued archival of oceanographic data from ships and buoys, development of data-assimilation models to cover gaps in observational data, and continued funding and renewal of satellite temperature, wind, and ocean color programs to ensure continuous time series of physical and biological variables.

References

Ballance, L. T., R. L. Pitman, L. B. Spear, and P. C. Fiedler. 2002. Investigations into temporal patterns in distribution, abundance and habitat relationships within seabird communities of the eastern tropical Pacific. SWFSC Admin. Rep., La Jolla, LJ-02-17, 79 p.

DeNiro, M. J., and S. Epstein. 1978. Influence of diet on the distribution of carbon isotopes in animals. *Geochimica Cosmochimica Acta* 42: 495-506.

DeNiro, M. J., and S. Epstein. 1981. Influence of diet on the distribution of nitrogen isotopes in animals. *Geochimica Cosmochimica Acta* 45: 341-331.

Estrada, J. A., A. N. Rice, M. E. Lutcavage, and G. B. Skomal. 2003. Predicting trophic position in sharks of the north-west Atlantic Ocean using stable isotope analysis. *J Mar Bio Ass UK* 83: 1347-1350.

Fiedler, P. C. 2002. Environmental change in the eastern tropical Pacific Ocean: Review of ENSO and decadal variability. *Marine Ecology Progress Series* 244: 265-283.

Fiedler, P. C., and V. A. Philbrick. 2002. Environmental change in the eastern tropical Pacific Ocean: Observations in 1986-1990 and 1998-2000. SWFSC Admin. Rep., La Jolla, LJ-02-15, 16 p.

Gerrodette, T., and J. Forcada. 2002. Estimates of abundance of Western/Southern spotted, whitebelly spinner, striped and common dolphins, and pilot, sperm and Bryde's whales in the eastern tropical Pacific Ocean. SWFSC Admin. Rep., La Jolla, LJ-02-20, 24 p.

Godley B. J., D. R. Thompson, S. Waldron, and R.W. Furness. 1997. The trophic status of marine turtles as determined by stable isotope analysis. *Marine Ecology Progress Series* 166: 277-284.

Hobson, K. A. 1993. Trophic relationships among high Arctic seabirds: insights from tissue-dependent stable isotope models. *Marine Ecology Progress Series* 95: 7-18.

Hobson, K. A., D. M. Schell, D. Renoug, and E. Noseworthy. 1996. Stable carbon and nitrogen isotopic fractionation between diet and tissues of captive seals: implications for dietary reconstructions involving marine mammals. *Can. J. Fish. Aqua.t Sci.* 53: 528–533.

Kurle C. M., and G. J. Worthy. 2002. Stable isotope assessment of temporal and geographic differences in feeding ecology of northern fur seals (Callorhinus ursinus) and their prey. *Oecologia* 126: 254-265.

McGowan, J. A., D. R. Cayan, and L. M. Dorman. 1998. Climate-ocean variability and ecosystem response in the northeast Pacific. *Science* 281: 210-217.

Michener, R. H., and D. M. Schell. 1994. Stable isotope ratios as tracers in marine aquatic food webs. In: Latja K, Michener RH (eds) Stable isotopes in ecology and environmental science. Blackwell, Oxford. Pp 138-157.

Miller, A. J. and D. R. Cayan. 1994. The 1976-77 climate shift of the Pacific Ocean. *Oceanography* 7: 21-26.

Miniwaga, M., and W. Wada. 1984. Stepwise enrichment of d^{15}N along food chains: further evidence of the relation between d^{15}N and animal age. *Geochimica Cosmochimica Acta* 48: 1135-1140.

Napp, J. M., C. T. Bair, R. D. Brodeur, K. O. Coyle, N. S. Shiga, and K. Mier. 2002. Interannual and decadal variability in zooplankton communities if the southeast Bering sea shelf. *Deep-Sea Research II* 49: 5991-6008.

Peterson B. J., and B. Fry. 1987. Stable isotopes in ecosystem studies. *Annual Review of Ecology and Systematics* 18: 293-320.

Pitman. R. L., L. T. Ballance, and P. C. Fiedler. 2002. Temporal patterns in distribution and habitat associations of prey fishes and squids. SWFSC Admin. Rep., La Jolla, LJ-02-19, 52 p.

Reilly, S. B., P. C. Fiedler, T. Gerrodette, L. T. Ballance, R. L. Pitman, J. M. Borberg, and R. C. Holland. 2002a. Eastern tropical Pacific dolphin habitats - Interannual variability 1986-2000. SWFSC Admin. Rep., La Jolla, LJ-02-21, 44 p.

Reilly, S. B., L. T. Ballance, P. C. Fiedler, T. Gerrodette, R. L. Pitman, H. G. Moser, L. B. Spear, and J. M. Borberg. 2002b. Recent information to aid in detecting regime shifts in the eastern tropical Pacific Ocean. SWFSC Admin. Rep., La Jolla, LJ-02-22, 21 p.

Ruiz-Cooley, R. I., D. Gendron, S. Aguíñiga, S. Mesnick, and J. D. Carriquiry. 2004. Trophic relationships between sperm whales and jumbo squid using stable isotopes of C and N. *Marine Ecology Progress Series* 277: 275-283.

Stephens, C., S. Levitus, J. Antonov, and T. Boyer. 2001. On the Pacific Ocean regime shift. *Geophysical Research Letters* 28(19): 3721-3724.

Thomas, C. J., and L. B. Cahoon. 1993. Stable isotope analyses differentiate between different trophic pathways supporting rocky-reef fishes. *Marine Ecology Progress Series* 95: 19-24.

Venrick, E. L., J. A. McGowan, D. R. Cayan, and T. L. Hayward. 1987. Climate and chlorophyll a: long-term trends in the central north Pacific Ocean. *Science* 238: 70-72.

Wade, P.R., G. M. Watters, T. Gerrodette, and S. B. Reilly. 2007. Depletion of spotted and spinner dolphins in the eastern tropical Pacific: modeling hypotheses for their lack of recovery. *Marine Ecology Progress Series* 343: 1-14.

North Pacific Highly Migratory Species

Authors:
Sam McClatchie, Heidi Dewar, Suzanne Kohin, and Steven Bograd
(Southwest Fisheries Science Center)
Evan Howell
(Pacific Islands Fisheries Science Center)

Introduction

Under Article 64 of the United Nations Convention on Law of the Sea highly migratory species (HMS) are specifically defined. Based on this definition, the Pacific Fishery Management Council's (PFMC) HMS Management Plan specifies active management of the following species: Tunas [North Pacific albacore (Thunnus alalunga), *yellowfin* (T. albacares), *bigeye* (T. obesus), *skipjack* (Katsuwonus pelamis) *and northern bluefin* (T. thynnus orientalis)], *pelagic sharks [common thresher* (Alopias vulpinus), *pelagic thresher* (A. pelagicus), *bigeye thresher* (A. superciliosus), *shortfin mako* (Isurus oxyrinchus) *and blue* (Prionace glauca)], *billfish [striped marlin* (Tetrapturus audax) *and Pacific swordfish* (Xiphias gladius)] *and dolphinfish* (Coryphaena hippurus). *Although the PIFSC FMP includes additional species, this section, which includes work of the SWFSC and PIFSC, focuses on the above species.*

One of the greatest challenges facing fisheries biologists is predicting how long-term climate change will impact the distribution and abundance of marine organisms, including highly migratory species (HMS). Climatic impacts on HMS occur on a variety of space and time scales. These scales can be classified as long-term climate trends like global warming, multi-year climate cycles like the Pacific Decadal Oscillation (PDO), climate pulses such as ENSO, and higher frequency inter-annual and seasonal variability. While efforts to integrate oceanographic information with fisheries data or biological studies have illuminated climate impacts over shorter time-scales, impacts over longer time-scales have been more challenging to address. Even for variations such as regime shifts, there are few data with sufficiently long time series to accurately determine their effects. For taxa such as some pelagic fish or foraminifera that leave abundant scales or tests in the sediment, long-term variability can be deduced from sedimentary records (Soutar and Issacs, 1969; Baumgartner et al., 1992). Long-term fluctuations in other species can only be inferred from more recent correlations among species. Unfortunately, for the HMS defined by the management plan little or no information can be obtained from the paleo-oceanographic records, and therefore the effects of climate change may best be understood by studying the effects of higher frequency climate variability (eg. El Niño) on key habitats.

Climate Induced Ecosystem Concerns

The impacts of long-term climate change will undoubtedly be apparent at a number of different levels. Three important areas where substantial impacts are expected based on experience over shorter-time frames include recruitment, geographic range, and response to meso-scale features such as eddies and fronts that are a key determinant in distribution patterns within a region. Hence, the major climate induced ecosystem concerns for North Pacific HMS are:

I. Effect of climate variability on recruitment
II. Effect of climate variability on HMS habitats – changes in range and abundance
III. HMS responses to mobile oceanic gradients: fronts and meso-scale features

I. Effect of climate variability on recruitment

Description

Recruitment is one critical aspect of HMS biology that will likely be impacted by climate change regardless of life history strategies. A broad range of oceanographic and climactic factors can impact recruitment including temperature, wind shear, meso-scale features, temporal or spatial shifts in optimal habitat, upwelling, and salinity to name a few. The forcing mechanisms, however, will likely differ between sharks that bear few relatively large young, and broadcast spawners like tuna and billfish.

The majority of research conducted to date has examined the recruitment of broadcast spawners, and some insights into the potential impacts of climate change are available. The recruitment of relatively closely related species can respond differently to climate pulses or trends. For instance, temperate and tropical tuna appear to respond differently to pulsed climate variability. Temperate albacore recruitment was enhanced when La Niña conditions were dominant and the PDO was negative, with a two-year lag. In contrast, the tropical skipjack and yellowfin tuna showed enhanced recruitment when El Niño dominated (and the PDO was positive) with a one-year lag (Lehodey et al., 2003). Forcing mechanisms that impact the recruitment of one species may vary between locations. Modeling results indicate that the positive effects of El Niño on skipjack recruitment differ between the central and western Pacific. In the central region, the main factor is the westward extension of the equatorial warm pool. In the western region, the positive effect on recruitment is due to enhanced primary production in warmer water, and subsequent development of improved tuna forage conditions (Lehodey et al., 2003).

An example suggesting climatic effects on the northern bluefin tuna population is a positive correlation between the winter North Pacific Index (NPI) and bluefin recruitment for the period 1952-1998. The NPI provides a measure of the intensity of the mean wintertime Aleutian Low that influences both oceanography and climate. The mechanisms underlying the correlation remain unknown (Uehara et al., 2002).

Current Activities

1) Tunas and billfishes are broadcast spawners with extremely high egg production and repeated spawning activities that rely on quasi-permanent oceanographic features conducive to larval development. For both of these HMS groups, shipboard molecular identification of eggs and larvae is being conducted annually off Hawaii resulting in the characterization of spawning areas and spawning times. A better understanding of the oceanographic and climactic conditions conductive for spawning and larval recruitment is critical to understanding how these may change in time or space with climate change.

2) In the Southern California Bight annual fisheries independent surveys are being conducted to estimate the abundance of juvenile blue, mako and thresher sharks. Current efforts are focused on determining how environmental conditions influence catch per unit effort. Over the long-term, this will provide important insight into the impact of climate and oceanography on shark recruitment, a topic for which little is known.

Research Needs

Efforts to predict climate impacts on recruitment first require basic information about temporal and spatial patterns in spawning and recruitment and second, an understanding of how these are dependent on environmental conditions. Priority research needs to accomplish this are:

1) Increase efforts to examine the recruitment of pelagic sharks, which are managed under the HMS FMP and under international treaties. This should include fishery-independent surveys as well as more extensive use of Pacific wide-observer programs to examine the spatial distribution and relative abundance of neonates and juveniles and the reproductive biology of incidentally caught adult sharks. Far less is known about shark recruitment than broadcast spawners.
2) More comprehensive surveys of early life history phases of all HMS North Pacific-wide are required. This will require coordination among international management agencies and research institutions, but is required to obtain more comprehensive and systematic coverage over the Pacific.
3) Results from surveys need to be coupled with information on oceanography to understand the essential habitat of HMS during all life history phases.
4) Linking understanding of the essential habitat of pre-recruit HMS to predictions of how global climate change will impact physical and biological oceanography is needed to predict the future effects on recruitment.
5) Conduct research necessary to quantify the impact of atmospheric effects, such as weather and wind shear, on the recruitment of HMS. These are known to vary under different climate regimes.
6) While temperature is often considered an important determinant of spawning and recruitment due to correlations between spawning locales and temperature, other climate related features such as the oxygen minimum zone, thermocline depth, salinity, ocean circulation and possibly ultraviolet penetration also may impact recruitment. Additional research is required to determine the interplay between the different environmental factors in their impact on recruitment.

Resource Needs

1) Funding to further develop the tuna/billfish molecular ID protocol is needed. The methods were initially developed at SWFSC and are currently being employed on a limited basis.
2) Provide additional resources to conduct more comprehensive Pacific-wide surveys of shark reproductive biology using observer programs and fisheries independent sampling programs. This is currently conducted on a small-scale in the California Swordfish Drift Net Fishery.
3) Additional ship-time and personnel are needed to conduct larval surveys. This will complement existing surveys that are limited in both time and space.
4) More advanced models to forecast recruitment based on predicted changes in oceanography and climate are needed.
5) Additional resources to conduct focused studies on of the impact of a range of oceanographic and climate driven factors on recruitment are needed.
6) Expanded capability in the use of conventional and molecular identification methods for eggs and larvae of tunas, billfishes and tuna-like species managed under the HMS FMP

and under international treaties. This will dramatically improve the ability to conduct surveys for both eggs and larvae.

Climate Information Needs

- Increase ability to predict the impact of climate change on regional climate and oceanography in 4 dimensions.
- Additional information on regional weather and wind shear to incorporate into recruitment models.

II. Effect of climate variability on HMS habitats – changes in range and abundance

Description

Changes in the geographic range and abundance of HMS populations can be expected with climate change based on experience with other organisms and communities as well as documented responses to shorter-scale climate fluctuations like ENSO. The list of factors that are known to influence the range and abundance of marine organisms is quite long and likely varies throughout the life history of the animal. One of the most important environmental factors is temperature; others include prey availability, water column profiles of oxygen, and meso-scale features (see below). Of these, the one that has received the most attention in a climate change context is temperature. Tropical oceans have warmed by 1-2°C over the past 100 years (Hoegh-Guldberg, 1999) and climate predictions suggest that this is likely to continue for at least another 50 years (Hoegh-Guldberg, 1999). Such warming will likely lead to poleward shifts in the distribution of many HMS. The geographic range of HMS and/or their population sizes could either expand or contract.

Concurrent with the warming of the subtropical gyres we are seeing changes in ocean biology. A recent study using a 9-year time series of SeaWiFS ocean color found that the least productive oligotrophic gyres, those with surface chlorophyll is less than 0.07 mg/m^3, have expanded in area in the North Pacific, North Atlantic, South Pacific and South Atlantic by an average of 1-4%/yr (Polovina et al., 2008).

The long-term increase in temperature is overlain by ENSO effects that may produce additional temporary changes in the range of HMS. For example, skipjack dominate tuna catches in the western Equatorial Pacific warm pool. El Niño events produce a large zonal displacement of the warm pool that was linked to shifts in the skipjack population, with major implications for the fishery (Lehodey et al., 1997) as well as its effects on recruitment as noted above. Bigeye tuna in the central Tropical Pacific are also observed to respond to this ENSO-driven displacement of the warm pool. An increase in bigeye catch rates in the Hawaii-based longline fishery corresponding to an increase in eastward advection of the warm pool was observed during the winter months of El Niño events (Howell and Kobayashi, 2006). This eastward advection of warm pool waters, coupled with vertical changes in habitat, appeared to increase the availability of bigeye tuna to the longline fishery. This variability in bigeye availability is important as the central tropical Pacific represents only a small area fished by the Hawaii Longline Fishery, yet accounts for a large percentage of the total bigeye landings.

Shifts in the range of species can also lead to changes in community structure. HMS can leave areas that are no longer suitable habitat and some species change their range more quickly than others. Therefore, the community composition both in the historic and invaded range may evolve as a result of population movements. HMS can be impacted by temporal and spatial changes in community structure. For example, if migrations are timed to take advantage of a specific pulse of production that is shifted in time or space, expected prey may not be available. As mentioned above, similar scenarios could impact recruitment.

As top predators in the marine environment, pelagic sharks are likely to be greatly affected by changes in the distribution or abundance of their prey. Based on electronic tagging data, adult and sub-adult blue, mako and thresher sharks all have fairly wide thermal ranges suggesting that they may be able to change their vertical or horizontal distribution in response to climate induced changes in water temperatures (Weng and Block, 2004; Weng et al., 2005; S. Kohin, personal communication). Most also feed on a wide variety of prey and therefore may be able to shift their diet if some prey becomes unavailable. However, many of these species have discrete pupping areas, and neonates may be more susceptible to changes in water temperatures or oceanographic conditions.

Some of the best data available for examining interannual variability in migratory patterns of these pelagic sharks comes from ongoing electronic tagging studies. NMFS and the Tagging of Pacific Pelagics (TOPP) program have been studying movements of blue, mako and common thresher sharks since 2002. While the data are still being analyzed, some patterns have emerged. Shortfin mako sharks, for example, are strongly associated with the California Current and migrate along the U.S. and Baja California, Mexico coast. Sharks tagged during the summers of 2003, 2005 and 2006 migrated along the coast for the subsequent year, generally remaining within 100 miles of shore. However, sharks tagged in 2004 and tracked through summer 2005 tended to migrate farther from the coast and in a more dispersive manner than during the other years (S. Kohin, personal communication). A similar pattern was observed for the California sea lion which also forages within the California Current (Weise et al., 2006). Behavior of the mako sharks and sea lions may have been altered during 2004-2005 in response to the changes in the timing of coastal upwelling and a decrease in prey availability (Weise et al., 2006; Brodeur et al., 2006). Examinations of inter-annual variability in migratory patterns for blue and thresher sharks are currently underway.

Availability of North Pacific bluefin tuna to U.S. fishers in the eastern North Pacific has declined dramatically in recent decades. One possible explanation is that the portion of bluefin that migrate to the eastern Pacific has declined in response to shifts in prey abundance. Decadal scale variation in population abundance of Japanese sardine has been linked to the Pacific Decadal Oscillation (PDO). In the 1980s and early 1990s the availability of Japanese sardine (*Sardinops melanosticta*), an important prey of bluefin tuna in the western Pacific, was high due to favorable environmental conditions. Consequently, during the 1980s and early 1990s, bluefin tuna may have remained in western Pacific waters rather than migrating into the eastern Pacific (Polovina, 1996). More recently, the abundance of sardines off Japan has declined, but whether bluefin tuna availability in the eastern Pacific has increased has not been quantitatively examined.

Bigeye tuna is another important species which is targeted by commercial fisheries in the Pacific Ocean. When used together, data from fisheries logbooks and archival/satellite tags provide information on the movement, migration, and vertical behavior patterns of bigeye tuna. Musyl et al. (2003) used data collected from archival tags on bigeye around the Hawaiian archipelago to uncover differences in vertical behavior. In this study large differences in bigeye depth distibutions were found between day and night periods, as well as in times when animals associated with fish aggregating devices (FADs) or in varying oceanic environments. Using these same archival tags Sibert et al. (2003) were able to estimate horizontal movement patterns for this area close to the Hawaiian Archipelago. From these tagging studies, as well as ongoing research, a more precise habitat description for bigeye tuna will be possible. A better understanding of the preferred habitat of bigeye tuna will aid in understanding the effects of changing climate conditions. For example, an increase in surface temperatures and stratification may affect both the horizontal and vertical distribution patterns of this species in the central North Pacific.

The distribution of striped marlin (*Tetrapturus audax)*, like many of the HMS, is apparently related to temperature. While a few studies have reported changes in catch rates of striped marlin during El Niño events, the results differ depending on the area examined. Off Southern California and Baja California, Mexico, recreational catch of striped marlin increased during the 1983 and 1992 El Niños (Squire, 1987; Hammann et al., 1995). In contrast, a preliminary analysis of data from the east coast of Australia indicated increased catch rates during La Niña conditions (Wise and Bromhead, 2004). Differences may depend on whether the area under consideration is at the colder extreme or warmer extreme of the species range. Near the colder extreme, El Niño may cause an increase in abundance as the fish range into the transiently warmer waters, whereas at the warmer extreme, fish may move out of the area as waters become too warm. Recent electronic tracking data also show that striped marlin are predominately epipelagic, spending most of their time in the mixed layer, so climatic changes that affect the depth of the thermocline may also affect their distribution and behavior.

Current Activities

To understand how the geographic range or abundance of HMS might shift due to climate change requires an understanding of their current and historic range and abundance. Much of the work conducted by the HMS groups at NOAA focuses on these issues as well as linking results to environmental conditions to distinguish between human and environmental impacts on populations.

1) NOAA Fisheries routinely maintains long and short-term time-series of fisheries catch data for both target and non-target species, of data from fishery independent surveys, and of recreational catch and effort. Activities are ongoing to improve, standardize and modernize the acquisition of fisheries data. These data are all critical for defining stock structure and conducting assessments that provide insight into abundance and distribution.
2) Both electronic and conventional tagging programs to define essential habitat are ongoing. Electronic tagging studies of a number of North Pacific HMS have now been conducted for over five years, allowing for analysis of inter-annual differences linked to changes in environmental conditions. The PIFSC has an ongoing research project to tag bigeye tuna in the central North Pacific. Data has been transmitted from 45 popup satellite archival tags that were deployed on bigeye in locations within the extent of the Hawaii Longline fishery. Work is being done now to quantify the regional and seasonal variation in horizontal and vertical behavior for these animals. An examination of seasonal climactic shifts can also provide insight into the impacts of climate change.
3) Trophic studies are being conducted to establish the links between HMS and prey and how distribution of HMS might be linked to prey. Samples are being obtained from both commercial and recreational fisheries from a number of HMS in U.S. waters.
4) Additional efforts are ongoing to conduct stock assessments for many of the HMS species. For those species, recruitment strength is estimated based on virtual population analyses, or length/age structured stock assessments. Recruitment trends can be examined with respect to short and long-term climate changes.

Research Needs

Priority research needs are:

1) Identify and characterize essential habitat of HMS by combining satellite and *in-situ* oceanographic data with conventional tagging data, electronic tagging data, fishery data and fishery-independent resource surveys. This will help us to understand how environmental variability affects the distribution and abundance of selected HMS especially over longer time scales. To obtain Pacific-wide data will require better international coordination of fisheries databases and observer programs.
2) Expand the above analyses to include additional data sources for key prey species to better understand links between predator and prey abundance and distribution. This should include more comprehensive studies of the deep scattering layer (DSL), which is poorly understood especially in the context of environmental variability. The DSL is a critical food source for many HMS species. This effort would be advanced by improved communication and data sharing between groups working on HMS and mid-trophic level organisms.
3) Link defined essential habitat to predictive models of how climate change will impact oceanography including the abundance and distribution of both predator and prey.
4) Develop more complex tags that measure a range of environmental variables such as oxygen concentrations or behaviors like feeding or spawning. Efforts are ongoing at SWFSC to develop an acoustic tag that will measure prey fields. This will provide more comprehensive data on what is essential habitat.
5) Develop predictions of how longer term climate change will influence the timing and intensity of shorter-term events, including seasonal processes such as coastal upwelling and ENSO.

Resource Needs

Additional resources and personnel are required to enhance the current studies identified above and obtain a more comprehensive understanding of essential habitat and of the links between the environment and the abundance and distribution of predator and prey. This is a necessary precursor to predicting how abundance and distribution will be impacted by climate change. Specific needs are:

1) Better software and models to allow for quantitative analysis of fisheries and tagging data (historical and more recent) in relation to environmental conditions, both surface features and water column profiles. This is currently not readily available and hampers efforts to quantify relationships and link the diverse datasets. Current efforts are time consuming and less quantitative than will be required to predict the impacts of climate change. This will require additional qualified personnel.
2) Additional funding for more comprehensive surveys of mid trophic level organisms that are prey for HMS including the DSL. This ties in well to recent efforts to enhance acoustic sampling methods for the California Current region. What is needed is multi-frequency acoustics (12, 38, 120 and 200 kHz) capability on the new research vessels (with transducers mounted in a drop keel or in a tow-body).
3) Additional resources to maintain ongoing deployments of conventional and electronic tags on targeted HMS species. Tagging studies are among the most effective in

monitoring changes in species range and distribution in relation to environmental variability.

4) To complement acoustic surveys, better *in-situ* sampling methods are required. For example a high-speed, opening-closing trawl capable of sampling micronekton could be used for acoustic target identification. This would be of great value especially for efforts to sample the DSL. No similar net is currently available at the SWFSC for work in the eastern North Pacific, however some DSL sampling has been done by the PIFSC on the south Pacific albacore fishing ground near American Samoa.
5) There is currently a large archive of historic data that is not in electronic format and consequently cannot be easily accessed. This includes acoustic survey data collected by CalCOFI. Funding is required to process this type of data so that it can be distributed and analyzed in relation to environmental conditions.
6) More complex stock assessments to incorporate both electronic tagging data and environmental conditions to help distinguish between the impact of environment and human activity and identify which environmental factors influence the abundance of HMS. This will require additional staff for the stock assessment group.
7) Additional funding to improve and standardize the collection of fisheries data from around the globe. Current efforts are slowed by too few qualified staff.

Climate Information Needs

- As with recruitment, we need better information on how climate change will influence regional climactic and oceanographic conditions including water column profiles of key parameters. Coastal regions, especially in the California Current, are of particular importance. Collection of core oceanographic variables would require a sustained ocean observing network, such as that planned for the Pacific Coastal Ocean Observing System (PaCOOS).

III. HMS responses to mobile oceanic gradients: fronts and meso-scale features

Description

Marine organisms are not randomly distributed throughout the world’s oceans but instead are uneven and patchy. This patchy distribution is often driven by meso-scale features. Very small gradients can be associated with major changes in the distribution of HMS. Small changes in oceanic conditions forced by climate variability at all temporal scales (trend, regime shift, pulses and interannual) will likely affect the location, intensity and persistence of oceanographic features over a range of spatial scales. Any such changes can impact the suitability of these features as habitat for organisms at all life history stages. For example, modeling suggests that the recruitment of sardines in the California Current can be both positively and negatively affected by the abundance of meso-scale eddies (Logerwell and Smith, 2001). It is likely that

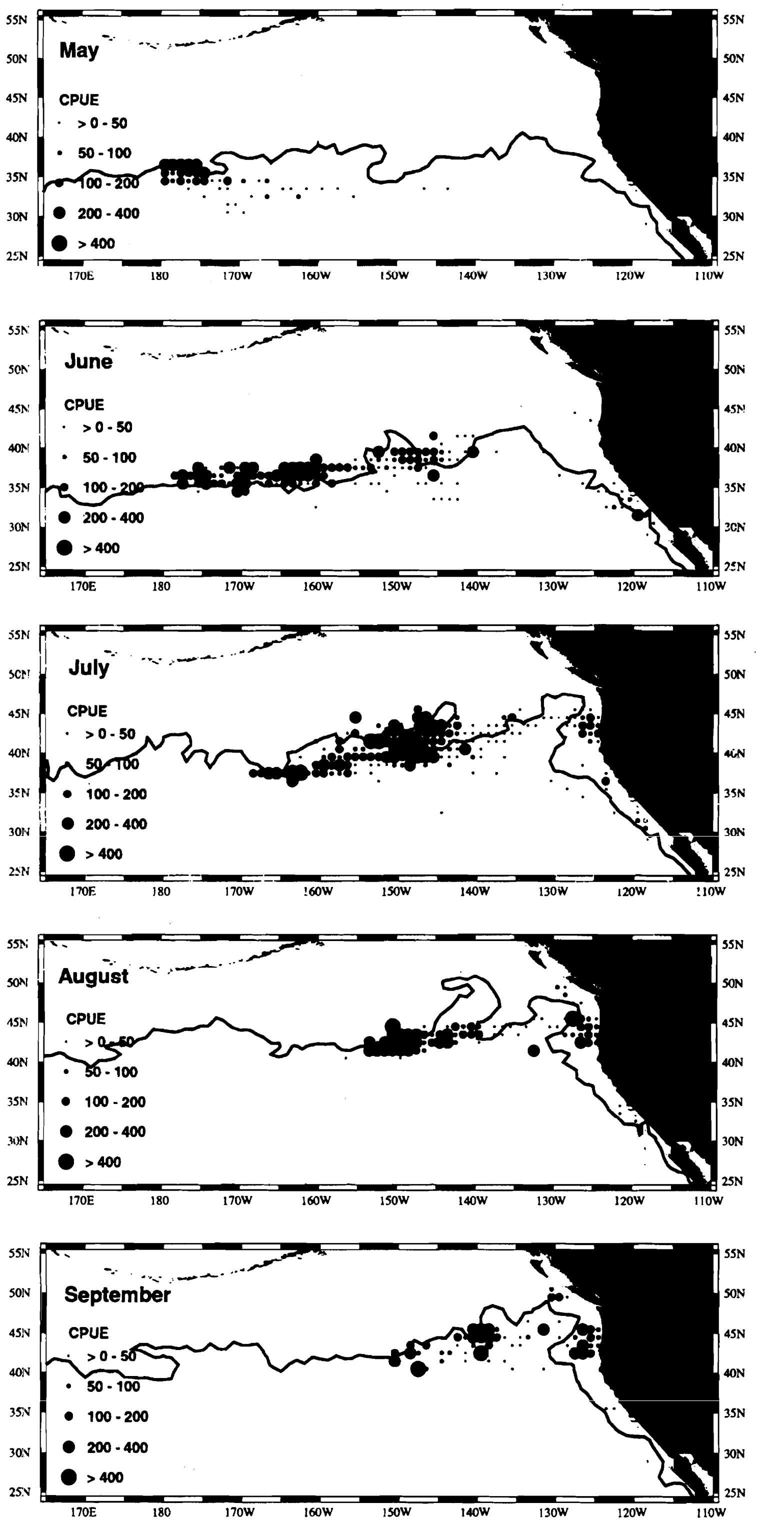

Figure 1: from Polovina et al., 2001: The meandering solid line shows the TZCF (0.2 mg m^{-3}) chlorophyll *a* and dots show the spatial distribution of albacore CPUE from the U.S. troll fishery for May – September 1998. Note how the albacore seasonal migration follows the TZCF.

other small pelagics would show similar responses, changing the available forage for HMS. Climate forced changes in the North Pacific Transition Zone Chlorophyll Front, a basin-wide feature which moves between about 35^{o}N in summer and 45^{o}N in winter, would be expected to have a significant impact on the foraging of loggerhead turtles, as well as on the seasonal migration and distribution of albacore, bluefin tuna and other HMS which follow the front as they migrate (Polovina et al., 2001) (Figure 1). Similarly, the location of biological hotspots such as that observed off southern Baja California (Etnoyer et al., 2004) could change, affecting the catch rates of billfish and the location where whales stop to feed during their long-distance movements. Etnoyer et al. (2004) compared the frontal energy during El Niño and La Niña in the North Pacific, revealing some interesting differences under the two climactic conditions. The annual frontal energy was lower both off the Channel Islands and southern Baja California, Mexico during the El Niño and higher during La Niña, with the reverse being the case in the North Pacific Transition Zone (Figure 2). Whales tracked off the U.S. West Coast spent less time off southern Baja during the El Niño, suggesting a reduction in local productivity during this climactic event.

Because swordfish (*Xiphias gladius*) are targeted by commercial fisheries throughout the Pacific Ocean, the most complete information on climate effects comes from analysis of fisheries data. In the central North Pacific, highest catch rates occur in association with the frontal zones bounding the North Pacific transition zone, even when gradients in temperature are very slight (Bigelow et al., 1999). In this study, frontal energy was also an important predictor of catch rate, but not as important as SST. In the coastal regions around the Pacific, catch is highest in areas with high frontal energy (Sakagawa, 1989). Patterns in one of these frontal areas off California illustrate that temperature also plays a role in distributions. Here, swordfish fisheries are seasonal, with the highest catch rates in the summer and fall when temperatures are the warmest. In addition, during El Niño years, the distribution of swordfish extends to higher latitudes in both the northern and southern hemisphere (Caviedes, 1975; Brosnan and Becker, 1998). One challenge in linking swordfish abundance and distribution to climate has to do with their

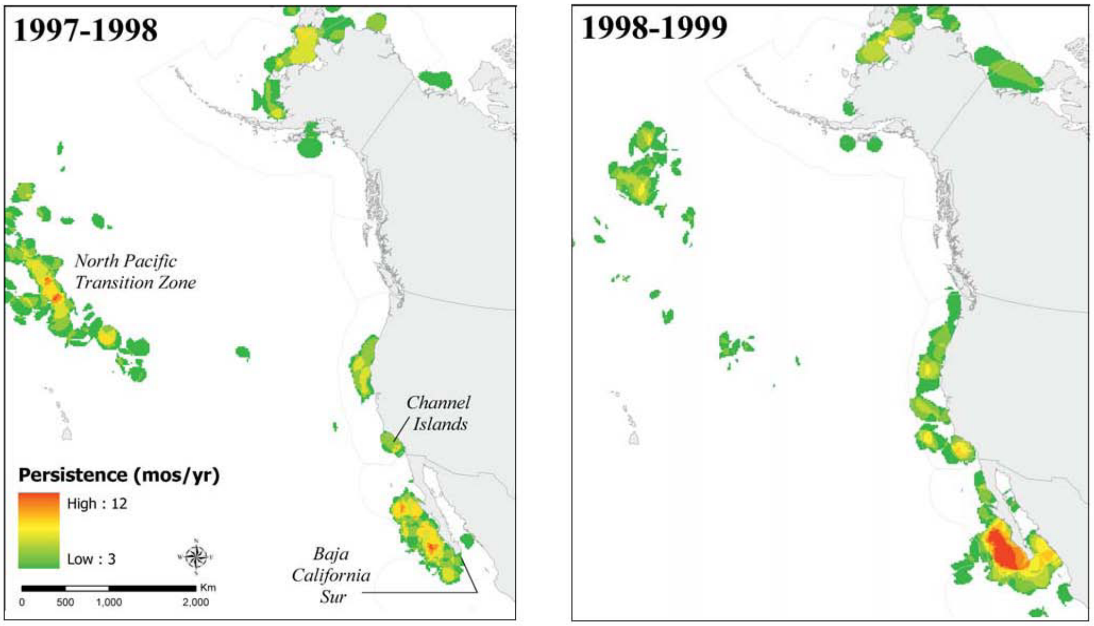

Figure 2: from Etnoyer et al., 2004: Persistence, in months per year, for concentrations of sea surface temperature fronts in the Northeast Pacific. Red values indicate exceptional densities of temperature gradients: 12 months per year. Green values indicate seasonal concentrations. The years defined are June 1997-1998 (El Niño) and June 1998-1999) (La Niña).

foraging behavior. Swordfish forage largely on the DSL, spending the majority of their day at depths between 300 and 600 m. Their focus on this subsurface layer may limit the utility of using surface ocean features to understand their distributions and highlights the need to learn more about the links between surface features and the DSL.

Another species for which abundance is linked to meso-scale features is the North Pacific albacore. This stock ranges from 10-50°N latitude between Japan and the North American coast. A number of studies have demonstrated the dependence of albacore tuna on specific water temperatures and oceanographic conditions. In general, albacore show a preference for transition zone waters where SST, chlorophyll and salinity gradients tend to be high (Laurs and Lynn, 1991; Polovina et al., 2001). Surface mixing in transition zone areas creates meso-scale features that are thought to concentrate prey. The North Pacific Transition Zone (NPTZ), in addition to being important habitat for albacore, is also important for a number of other pelagic predators including seabirds, turtles, swordfish and bluefin tuna. Temporal changes in the location and/or strength of the frontal areas in the NPTZ or in association with El Niño conditions is highly correlated with changes in albacore migrations and distribution (Laurs and Lynn, 1991; Polovina et al., 2001; Kimura et al., 1997) and will likely affect the other predators as well.

Current Activities

As mentioned, the presence of meso-scale features can significantly impact regional abundance of HMS creating "hotspots" where either single or multiple species aggregate. Much of the current work to understand the impact of meso-scale features centers on the study of hotspots. Once hotspots have been characterized, analyses using archived oceanographic data will enable quantification of their climate driven variability.

1) In collaboration with the Tagging of Pacific Program, SWFSC is using electronic tagging data in combination with remote sensing and *in-situ* oceanographic observations to locate biologically important HMS hot spots, describe their physical characteristics, quantify their temporal persistence, and understand their impact on species behavior and interactions. Initial efforts are in the California Current where more than 23 species covering diverse taxanomic groups (birds, turtles, fish, and marine mammals) are being electronically tagged. Tagging spanned a mild ENSO event that should provide some insight into the potential implications of climate change.
2) Ultimately efforts at the SWFSC and PIFSC will be expanded to describe, and possibly forecast, oceanographic features, both physical and biological, that are associated with high concentrations of albacore and bluefin tuna in the central North Pacific (Kuroshio Current extension and sub-arctic transition zone). In the long-term these predictions can be linked to climate models.

Research Needs

A problem with predicting how HMS respond to climate change is our poor understanding of HMS habitat, especially in relation to dynamic ocean processes. Areas that are ripe for additional analyses include examining the electronic tagging datasets being collected for a range of HMS species, as well as the archives of fisheries data. These data should be examined with a focus on characterizing climate impacts on seasonal to decadal scales. This approach should be taken with the first three points listed below.

1) Expand efforts to quantify the links between meso-scale features and tracks obtained from electronic tags over long time frames. This is currently occurring on a limited basis.
2) Begin to examine long-term archives of fishery-dependent and -independent data in relation to meso-scale features
3) Additional information on how the abundance and distribution of HMS, their prey and the DSL varies in relation to fronts and meso-scale features is needed. This will require focused field and modeling studies.
4) Before we can accurately predict how climate change will impact HMS in the North Pacific we need a better understanding of how the environment responds to climate forcing over a range of spatial and temporal scales. Critical questions include how the major current systems might shift or change in intensity as well as how the processes driving meso-scale features, including fronts and eddies, will change.

Resource Needs

1) Staff to develop the software to rapidly integrate oceanography and atmospheric data with fisheries and electronic tracking data. Currently these efforts are labor intensive and developing quantitative relationships across a range of environmental variables is complicated. This is especially the case when it comes to meso-scale features and fronts where the persistence and intensity are both important. A further complication is that there often exists a lag between the time a front is created and when it becomes habitat for a given HMS. Quantifying these relationships will require complex software. This software should be developed such that it can be broadly distributed to the scientific community to make quantitative analysis more accessible.
2) Additional ship-time, personnel and equipment will be required for focused studies to establish the relationship between surface features and the abundance and distribution of the DSL.

Climate Information Needs

- Better information on how climate change will impact meso-scale features as well as large-scale current patterns. Critical information includes the intensity, persistence and temporal and spatial patterns of key oceanographic processes and features.

References

Baumgartner, T. R., A. Soutar and V. Ferreira-Batrina. 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 Reports 33: 24-40.

Bigelow, K. A., C. H. Boggs, and X. He. 1999. Environmental effects of swordfish and blue shark catch rates in the US North Pacific longline fishery. Fisheries Oceanography 8(3): 178-198.

Brodeur, R. D., S. Ralston, R. L. Emmett, M. Trudel, T. D. Auth, and A. J. Phillips. 2006. Anomalous pelagic nekton abundance, distribution, and recruitment in the northern California Current in 2004 and 2005. Geophysical Research Letters 33: L22S08, doi:10.1029/2006GL026614.

Brosnan, D., and C. Becker. 1998. El Nino southern Oscillations (Enso) and their impacts on marine populations. PALCO SYP.HCP VI Part B. http://resources.ca.gov/headwaters/hcp/v4/v4pbs6.pdf.

Caviedes, C. N. 1975. El Niño 1972: Its climatic, ecological, human, and economic implications. Geographical Reviews 65: 493–509.

Etnoyer, P., D. Canny, B. Mate, and L. E. Morgan. 2004. Persistent pelagic habitat in the Baja, California to Bering Sea (B2B) Ecoregion. Oceanography 17(1): 90-101.

Hammann, M. G., J. S. P. Nayar, and O. Sosa-Nishizaki. 1995. The effects of the 1992 El Niño on the fisheries of Baja California, Mexico. CalCOFI Reports 36: 127-133.

Hoegh-Guldberg, O. 1999. Climate change, coral bleaching and the future of the worlds coral reefs. Marine & Freshwater Research 50: 839-866.

Howell, E. A., and D. R. Kobayashi. 2006. El Niño effects in the Palmyra Atoll region: oceanographic changes and bigeye tuna (*Thunnus obesus*) catch rate variability. Fisheries Oceanography 15(6): 477-489.

Kimura, S., M. Nakai, and T. Sugimoto. 1997. Migration of albacore, *Thunnus alalunga*, in the North Pacific Ocean in relation to large oceanic phenomena. Fisheries Oceanography 6(2): 51-57.

Laurs, R. M., and R. J. Lynn. 1991. North Pacific albacore ecology and oceanography. NOAA/NMFS Technical Report 105: 69-87.

Lehodey, P., M. Bertignac, J. Hampton, and A. Lewis. 1997. El Niño Southern Oscillation and tuna in the western Pacific. Nature 389, 715-718.

Lehodey, P., F. Chai and J. Hampton. 2003. Modeling climate-related variability of tuna populations from a coupled ocean-biogeochemical-population dynamics model. Fisheries Oceanography 12(4/5): 483-494.

Logerwell, E. A. and P. E. Smith. 2001. Mesoscale eddies and survival of late stage Pacific sardine (*Sardinops sagax)* larvae. Fisheries Oceanography. 10(1): 13-25.

Polovina, J. J. 1996. Decadal variation in the trans-Pacific migration of northern bluefin tuna (*Thunnus thynnus*) coherent with climate-induced change in prey abundance. Fisheries Oceanography 5(2): 114-119.

Polovina, J. J., E. A. Howell, M. Abecassis. 2008. Ocean’s least productive waters are expanding. Geophys. Res. Lett. 35: L03618, doi:10.1029/2007GL031745.

Polovina, J. J., E. Howell, D. R. Kobayashi, and M. P. Seki. 2001. The Transition Zone chlorophyll front, a dynamic global feature defining migration and forage habitat for marine resources. Progress in Oceanography 49: 469-483.

Sakagawa, G. T. 1989. Trends in fisheries for swordfish in the Pacific Ocean. *In* Stroud, R.H. (ed) Planning the future of billfishes, research and management in the 90's and beyond. Part 1. Marine Recreational Fisheries 13: 61–79.

Squire, J. L. 1987. Relation of sea surface temperature changes during the 1983 El Niño to the geographical distribution of some important recreational pelagic species and their catch temperature parameters. Marine Fisheries Review 49: 44-57.

Soutar, A., and J. D. Issacs. 1969. History of fish populations inferred from fish scales in anaerobic sediments off California. CalCOFI Reports 13: 63-70.

Uehara, K., H. Yamada, K. Uosaki, and D. Inagake. 2002. Comparison of recruitment variability of Pacific bluefin tuna with global atmospheric-oceanic conditions associated with the El-Nino-Southern Oscillation (ENSO) phenomenon. Collective volume of scientific papers. International Commission for the Conservation of Atlantic Tunas 54(4): 992-1007.

Weise, M. J., D. P. Costa, and R. M. Kudela. 2006. Movement and diving behavior of male California sea lion (*Zalophus californianus*) during anomalous oceanographic conditions of 2005 compared to those of 2004. Geophysical Research Letters 33: L22S10, doi:10.1029/2006GL027113.

Weng, K. C., and B. A. Block. 2004. Diel vertical migration of the bigeye thresher shark (*Alopias superciliosus*), a species possessing orbital retia mirabilia. Fishery Bulletin 102(1): 221-229.

Weng, K. C, P. C. Castilho, J. M. Morrissette, A. M. Landeira-Fernandez, D. B. Holts, R. J. Schallert, K. J. Goldman, and B. A. Block. 2005. Satellite tagging and cardiac physiology reveal niche expansion in salmon sharks. Science 310: 104-106.

Wise, B., and D. Bromhead. 2004 Striped marlin abundance: standardisation of CPUE. Chapter 8 *In* Bromhead, D., J. Pepperell, B. Wise and J. Findlay (eds.) Striped marlin: biology and fisheries. Bureau of Rural Sciences, Canberra, Australia.

Antarctic

Author:
Christian Reiss
(Southwest Fisheries Science Center)

Introduction

NOAA Fisheries has conducted annual biological and oceanographic monitoring in the South Shetland Islands region of the Antarctic Peninsula, since 1986. Data collected as part of the monitoring effort is used to advise CCAMLR (the Convention for the Conservation of Antarctic Marine Living Resources) in setting catch limits of Antarctic krill (*Euphausia superba*), as well as several species of finfish, squid, and crab populations within the framework of this international harvesting Convention. Land-based predator population dynamics (three species of penguins and Antarctic fur seals) are also monitored, using a standardized series of biological measurements (CCAMLR Environmental Monitoring Program). CCAMLR employs an ecosystem-based approach to management and specifically requires that ecological relationships among harvested, dependent and related species be maintained. Thus, separating the effects of fishing from climate driven environmental variability is a critical component of the monitoring conducted by the Southwest Fisheries Science Center, U.S. Antarctic Marine Living Resources program (U.S. AMLR). This program is also timely, as the Antarctic peninsula area (Fig. 1), including the South Shetland Islands, is one of three regions on the planet that has experienced the most rapid and pervasive environmental changes over the last 50 years (Vaughan et al., 2003). This summary focuses on data from the south Atlantic sector of the Southern Ocean; the area in which the U.S. AMLR program has monitoring and scientific programs.

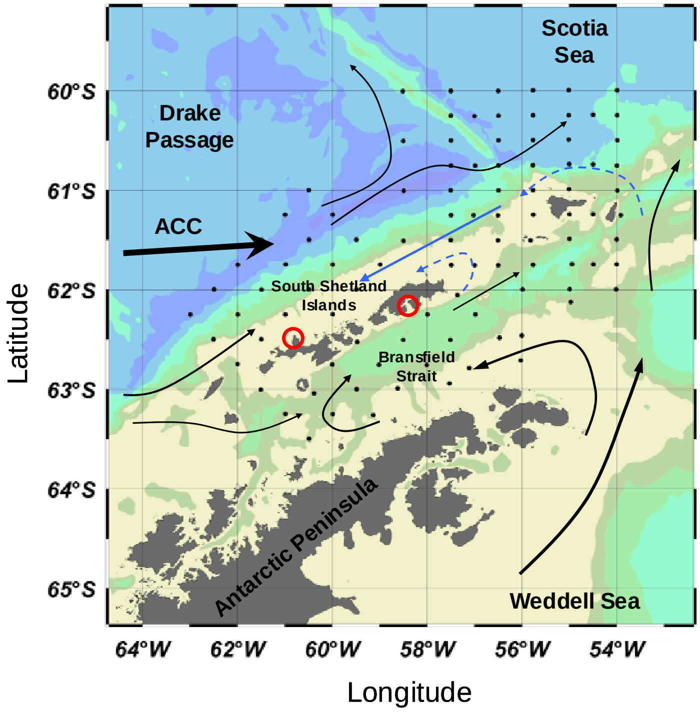

Figure 1. Bathymetric chart of the Antarctic Peninsula region including the West Antarctic Peninsula and the South Shetland Islands. Black dots represent fixed sample sites during U.S. AMLR acoustic biomass surveys. Open red circles represent locations of the Cape Shirreff and Copacabana field stations operated by U.S. AMLR and the U.S. NSF. Solid black lines represent prevailing flows, and blue lines represent surface counter current circulation. Depth contours are 500, 750, 1000, 1250, 2500, >2500 m.

Climate Induced Ecosystem Concerns

Within the U.S. AMLR area of the Southern Ocean the atmosphere/ocean/ecosystem is very tightly coupled and climate forcing impacts all trophic levels. Atmospheric climate scale variability drives air and sea temperature patterns (Turner et al., 2005; Sprintall, 2003), sea-ice dynamics (Zwally et al., 2002), variability in the Antarctic Circumpolar Current (ACC) strength (Meredith et al., 2004), the position of frontal features and the outflow from the Weddell Sea (Conil and Menendez, 2006) and influences Upper Circumpolar Deep Water (UCDW; Klinck, 1998). Winter ocean conditions are also important although much less is known about winter variability. Other atmospheric phenomena will impact the pH of the ocean, potentially impacting physiological calcium carbonate pathways in a variety of animals.

The major climate induced ecosystem concerns in order of importance are:

I. Ocean temperature, sea ice extent, and Weddell outflow variability
II. Circumpolar Current variability and Upper Circumpolar Deep Water movement
III. Winter ocean environment and its climatic variability
IV. Ocean acidification

I. Ocean temperature, sea ice extent, and Weddell outflow variability

Description

Both sea and air temperatures have experienced substantial changes over the short time that records exist (Gille, 2002; Turner et al., 2005). Within the open ocean environment, deep water temperatures appear to have increased ~0.2 ºC over the last 40 years (Gille, 2002). Winter and summer air temperatures along the coast of the Antarctic Peninsula have also increased (Turner et al., 2005). No significant long term trends in sea surface water temperature have been observed, although considerable variability in sea surface temperatures are associated with El Niño – La Niña events. Small deviations in water temperature have important impacts on biological processes in the Antarctic. For example, small changes in temperature and salinity have large impacts on water column stability and therefore primary productivity. In addition, enzymatic activities of many invertebrate species (including krill) are adapted to low temperatures, so water temperature increases are likely to impact energetic and physiological conditions at the base of the food chain.

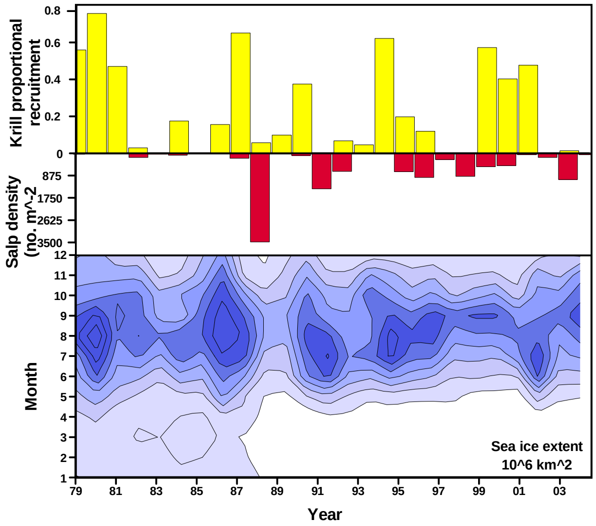

Figure 2. Time series plots of the proportional recruitment of Antarctic krill (upper panel; yellow), the abundance of salps (middle panel; red) and extent and duration of sea ice (bottom panel; blue high ice concentration). High proportional recruitment follows years of high ice extent and duration and salps increase during periods of low ice extent and duration.

Sea-ice is perhaps the most conspicuous physical feature of the oceanic environment that directly affects organisms in the Antarctic. Sea-ice provides habitat for ice dependent animals, serves as refuge from predation for some fish species, and contains algal communities that serve as nourishment during the over-wintering phase of juvenile krill (see review Garrison, 1991). Variability in the extent and duration of sea-ice, and it's relation to atmospheric events like El-Niño or other atmospheric forcing directly impacts a variety of species and communities.

U.S. AMLR studies (Loeb et al., 1997; Hewitt et al., 2003) have directly related recruitment variability of krill to amount of sea ice, with high recruitment following years of high sea ice extent and duration (Fig. 2). Additionally, the ecosystem switches from being krill dominated to salp dominated when sea ice concentrations are low. Since the late 1980s, sea ice duration has declined, and this has resulted in a corresponding increase in the number of salp dominated years.

Changes in the frequency of krill recruitment events are likely to greatly impact the populations of land based predators. In particular, strong correlations between indices of penguin and krill recruitment suggest that penguins in the South Shetland Islands may live under an increasingly krill-limited system that has disproportionate effects on the survival of juvenile penguins (Hinke et al., 2008)

In the West Antarctic Peninsula and South Shetland Islands (SSI) region sea ice duration has varied considerably, and the extent has generally declined over the last thirty years (Zwally et al., 2002). These changes may be associated with ambient environmental conditions, as sea ice extent is highly correlated with annual air temperatures (Turner, 2005; Fig. 3).

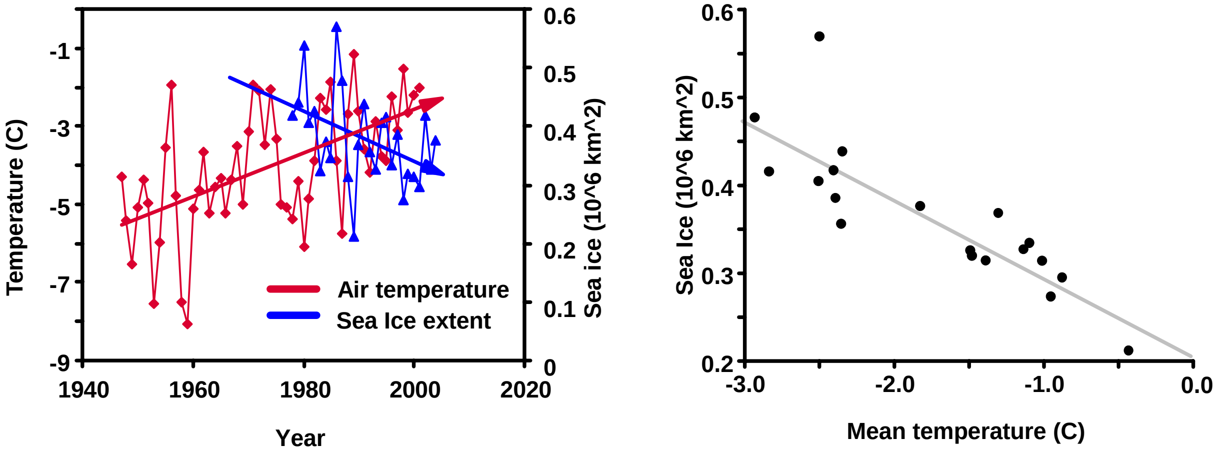

Figure 3. Relationship between air temperature and sea ice extent in the West Antarctic Peninsula and South Shetland Islands. A) Secular trends in air temperature and sea ice are significant ($p<0.05$); B) Sea-ice extent is highly ($p<0.001$) negatively correlated with air temperature over the period 1979 to 2005.

The effects of sea surface temperature variability are not limited to the effect on sea ice and krill productivity. Other atmospheric forcing mechanisms are associated with variability in phytoplankton biomass and the development of the spring bloom. Over the last 17 years U.S. AMLR has monitored the phytoplankton productivity of this area as krill are dependent upon phytoplankton for food, and for reproductive energy. El Niño is a major factor influencing phytoplankton productivity and the development of the spring bloom in the South Shetland Islands (Reiss, unpublished data.). Elevated indices of El Niño (the EN34 index) are associated with low chl *a* in the waters around the South Shetland Islands. Thus, broad scale climate variability critically impacts the structure and function of the Antarctic ecosystem, and ensures that separating the effects of climate variability from fishing will be complicated without detailed study and enhanced cooperation with climate programs.

The outflow and circulation of the Weddell Sea, which is adjacent to the South Shetland Islands, is directly impacted by global climate variability (Martinson and Ianuzzi, 2003; Conil and Menendez, 2006). U.S. AMLR has found that the balance between Weddell outflow and ACC influence may also impact the productivity of the waters around the South Shetland Islands (Reiss, unpublished data). During periods of low phytoplankton productivity, the water around

Elephant Island is slightly cooler and more saline, indicative of a Weddell source. Thus, understanding the variability in the outflow of the Weddell is critical to understanding the bottom up processes in this area.

Modeling studies indicate that over the next 20-30 years the Western Weddell Sea area, including the South Shetland Islands area, will encounter consistent increases in air temperature, coupled with increases in sea surface salinity. Such differences may impact the productivity of the SSI region by changing the outflow of the Weddell and by altering the stratification of the water column around the South Shetland Islands.

In addition to the pelagic environment, finfish populations monitored by the U.S. AMLR program are also likely affected by climate. However, in contrast to krill, most populations for which significant data exist show that populations that have been overfished have not increased greatly since the cessation of harvesting (Jones et al., 2000; Kock and Jones, 2005). There is little information about the effects of climate on most Antarctic fish stocks and species. The paucity of time series data reflects the huge area of the Southern ocean, and the relatively recent nature of most finfish fisheries in the region.

Some species of non-fished finfish show declines that may indicate changes in productivity associated with changing environments. For example, the notothenoid *Gobionotothen gibberifrons*, has demonstrated consistent declines in abundance and recruitment in the South Shetland Islands (Barrera-Oro et al., 2000; Barrera-Oro and Marschoff, 2007), which has been closed to commercial fishing since 1989/90 and is not being impacted by harvest. The conclusion is that some environmental change is responsible. This could be climate related, but may also represent changes in competition for resources among species.

Current Activities

In order to monitor and assess the impact of remote forcing of broadscale climatic variability on ocean temperature, sea ice extent and decline, and Weddell outflow variability, the U.S. AMLR program monitors summer surface and sub-pycnocline water properties at ~100 stations twice each summer. The nearly 20 year record of summer water temperature are approaching a sufficient length to resolve correlations with atmospheric teleconnections (ENSO), but are still too short to resolve decadal scale variability. However, no consistent monitoring of the western Weddell Sea is conducted by the U.S. AMLR program. Ice conditions and limitations of the chartered vessel have precluded establishment of long term monitoring stations from which to infer the strength of the Weddell outflow.

The U.S. AMLR program develops annual and seasonal sea-ice extent indices for the South Shetland Islands area for use in statistical models relating ice variability to recruitment of krill (Loeb et al., 1997; Hewitt et al., 2003). Additionally, we monitor air temperature from existing sites along the western Antarctic Peninsula, in order to extend time series of sea ice into the past.

Research Needs

The U.S. AMLR program continues to monitor summer water temperatures, and is developing indices of variability that may be useful in separating effects of *in situ* warming from water mass effects. Better automated sea surface and sub surface water temperature (i.e. of the top few hundred meters) would be extremely valuable to understand interannual variability in the water column temperature.

As satellite data recorders are placed on over-wintering seals and penguins, U.S. AMLR will develop and acquire a variety of remotely sensed indices of the environment. Satellite based sea surface temperature, chlorophyll and sea ice concentration and distribution as well as current velocities will provide the means to analyze these overwintering behaviors.

Further development of predictive models of the effects of sea-ice variability on biological populations will require significant resources. Our current vessel is incapable of operating within the ice thereby limiting our inferences about the importance of ice to krill and other organisms to an examination of variability as inferred from space. Outside line offices that model sea-ice dynamics for input into Global Circulation models (GCM) are critical partners in extending our program and understanding the biological and ecosystem consequences of sea-ice loss and variability.

One factor necessary for the interpretation of the data collected by U.S. AMLR is a quantitative ecosystem model to investigate the impact of climate variability on the whole ecosystem. Currently ecosystem models are being used to investigate options for the implementation of small-scale management units to the krill fishery. Models that examine the impact of climate variability across intermediate and long-term management timescales have not been developed.

Climate Information Needs

The U.S. AMLR program sees a number of opportunities to team with the climate program to better understand ecosystem variability attributed to these factors. Simple increases in the level of observation are critical. For example, fully autonomous weather stations within Bransfield Strait, at both the Copacabana, and Cape Shirreff field stations as well as at Elephant Island would be extremely important in understanding regional weather and climate impacts. Currently, the U.S AMLR program relies on data collected at weather stations farther to the southwest. Local conditions, including precipitation and incident PAR and surface water temperature, need to be measured locally and are critical to understanding the development of the spring bloom, and for the examination of energetics and reproductive success of krill dependent predators.

II. Circumpolar Current variability and Upper Circumpolar Deep Water movement

Description

The strength and variability of the prevailing Antarctic Circumpolar Current (ACC) is impacted by climatic forcing (Meredith et al., 2004). Meridional variability in winds originating from the Pacific basin drives the Southern Annular Mode of atmospheric variability which creates variability in the strength of the ACC. The strength of the ACC controls the amount of upwelling that occurs in response to the geostrophic adjustment. South of the Polar front, this upwelling may control the upward flux of limiting nutrients potentially impacting bottom up ecosystem functions like primary productivity. Additionally, due to the prevailing eastward flow of the ACC, local krill abundance downstream from the South Shetland Islands likely results from transport variability within the ACC (Loeb et al., 1997). Penguins and seals variously use the ACC to transit between feeding and reproductive sites, and may use the prevailing currents or eddies to minimize energy use, and travel time. Thus, understanding the variability in the strength of the ACC is likely to increase our knowledge of the interaction between advection and the abundance and distribution of krill and larger predators.

Current Activities

Currently, the U.S. AMLR program monitors the upper water column summer temperature of the ACC to 850m, between two and four times each summer. Additionally, the U.S. AMLR program in conjunction with the NOAA Vessel of Opportunity Program and the National Drifter Program at AOML, releases between 10 and 20 sea surface temperature drifters each summer, on transits across the Drake Passage.

Research Needs

Future integration into the large scale modeling programs within NOAA and especially the Geophysical Fluid Dynamics Laboratory, and outside ecosystem and climate programs including NASA and NSF will be critical to model the dynamics of the ACC and the Weddell outflow, and the interactions within the South Shetland Islands.

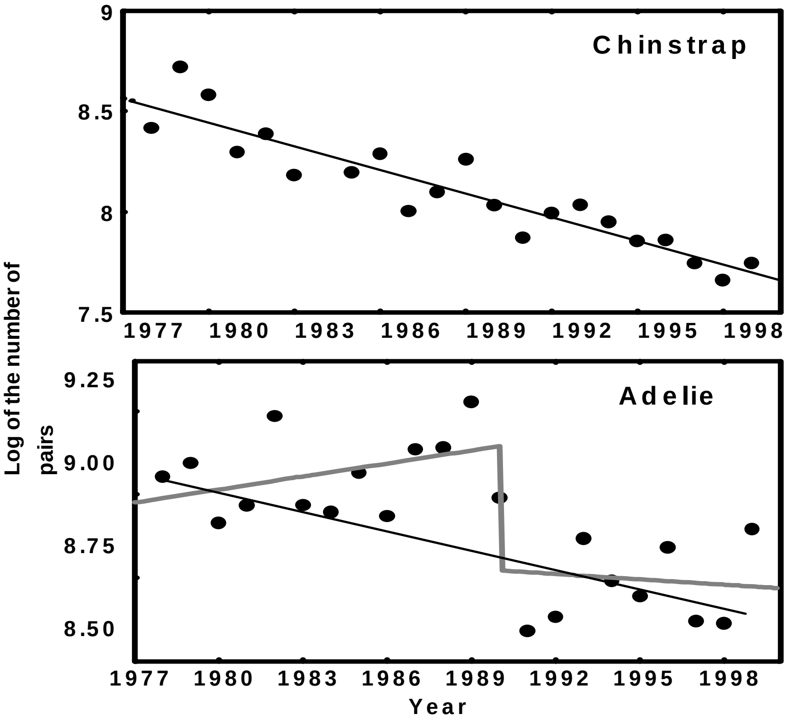

Figure 4. Population trends of Chinstrap and Adelie penguins at Copacabana, King George Island, 1978 - 1999. Black lines represent the linear regressions solid grey line represents the piecewise linear regression with breakpoint. Trends have continued through the present.

Climate Information Needs

Coupled atmosphere ocean models at appropriate spatial resolution (<<1km near coast) are required. No local scale models such as those developed for other areas of US interest have been developed. However, the NOAA climate program and OAR have the capacity and modeling expertise to develop these models in cooperation with U.S. AMLR.

III. Winter ocean environment and climatic variability

Description

Over the past 30 years, Gentoo penguin populations have remained fairly constant, while Chinstrap penguins have shown a long-term downward trend, and Adelie penguins have shown a step wise decline in abundance (Fig. 4). Different trends in abundance and recruitment indices for each species, despite generally similar indices of summer performance, suggest that winter conditions contribute to the divergent responses among the penguin species (Hinke et al., 2008). Moreover, recent data, based on satellite tagged animals, suggest that each species has distinctively separate wintering areas, further supporting the hypothesis that overwinter survival is likely the critical factor affecting population trends in these three species (Trivelpiece et al., 2007).

Juvenile survival of Antarctic fur seals, particularly during the first winter at sea, is a critical factor determining population growth (Goebel et al., 2006b). Mark-recapture data from fur seals at Cape Shirreff, Livingston Island from 1997 to present show highly variable cohort success (Goebel et al., 2006a). Two factors appear to be critical to juvenile survival in their first year: pre-weaning predation by leopard seals and the post-weaning environment. Leopard seals exert a strong top-down influence on fur seal populations and may be controlling population growth (Boveng et al., 1998). Leopard seals are ice dependent predators, and their local abundance in the South Shetland Islands is correlated with ice dynamics (Goebel, pers. comm.). During intermediate ice years, the local abundance of leopard seals is elevated, as the ice edge is in close proximity to the South Shetland Islands. However, preliminary studies by the U.S. AMLR program of post-weaning dispersal and survival indicate that the environment young fur seals wean into also has a strong influence on overall cohort success (Goebel, unpublished data). However little is known about the mechanisms responsible for the variability in over winter survival.

U.S. AMLR is currently involved in collaborations with UCSC (University of California-Santa Cruz) and the SMRU (Sea Mammal Research Unit, St. Andrews, Scotland) to use southern elephant seals (SES) as oceanographic sampling platforms. These wide ranging very deep diving mammals can carry instruments over winter that measure temperature and salinity continuously and to depths of up to 1,000 meters. SES are circumpolar and these data are providing temperature-salinity throughout the southern ocean and winter months (Biuw et al. 2007,).

The combined information from both seal and penguin studies shows that the largest gap in our knowledge of the life history of higher trophic levels is in understanding the environmental determinants overwinter survival. Given the dispersion of animals during winter, it is not feasible or necessary to establish a winter field monitoring component. It is necessary however, to track the spatio-temporal dispersion of animals in relation to currents, temperature and other biological properties. Much of this can be accomplished using satellite based tracking of animal movements. This task will require significant resources for satellite tags.

Current Activities

While biological data collected as part of the environmental monitoring program in CCAMLR provides important information during the summer reproductive season, quantifying mortality, diet and habitat use during the winter is clearly an important and unresolved issue for penguins and seals. Recent advances in technology for satellite tracking of penguins and seals over winter and remote sensing of the southern ocean using satellites will be crucial in understanding the links between healthy ecosystems, commercial fisheries, and climate variability.

Research Needs

Remote sensing of climate and weather parameters (sea level, winds, temperature and chlorophyll) and integration of these data into statistical models of habitat use will help to identify likely scenarios controlling overwinter survival. Cooperation with the NOAA climate program in the development and testing of remote measures to examine habitat use under different winter conditions should provide a framework to understand climate impacts on the overwinter distribution and survival of seabirds and mammals.

Climate Information Needs

U.S. AMLR will require basic weather and climatological data of the winter months, across the Southern Ocean. Recent data from chinstrap penguins show that their winter migrations can exceed several thousand kilometers in lineal distance. Thus near real time forecasting of weather, current and sea ice conditions are critical to understanding overwinter survival of penguins and seals. Such data will allow U.S. AMLR to conduct re-analysis of ocean conditions from returning seals and penguins.

IV. Ocean acidification

Description

Antarctic marine organisms may be particularly susceptible to the effects of ocean acidification. The Southern Ocean is predicted to be among the first areas to have its surface waters become undersaturated with respect to aragonite, a form of calcium carbonate utilized by some marine organisms, potentially by the year 2050 (Orr et al., 2005). Changes in ocean pH over the next 20 years are likely to impact species that inhabit subpycnocline waters. For example, the Blackfin icefish (*Chaenocephalus aceratus*), which is in the group of Antarctic fishes that are the second most valuable commercially (following *Dissostichus* spp.) in the Antarctic is a benthic egg brooder (Detrich et al., 2005). Changing pH and aragonite and calcite compensation depths (below the mixed layer) may greatly impact egg-mass integrity through the dissolution of the mucous bonds which maintain nest integrity. This could have significant and widespread impact on the population dynamics of this and similar species. It would also have implications to trophic connection within the Antarctic foodweb.

Current Activities

U.S.AMLR has begun collaborating with NOAA OAR and California State University San Marcos to monitor the total alkalinity, and dissolved inorganic carbon concentration in the South Shetland Islands. This effort is currently supported by CSU and NOAA-OAR.

Research Needs

The U.S. AMLR program continues to develop the monitoring capacity to examine the likely influence of changes in ocean acidity on the marine resources and marine sentinels of the Southern Ocean. Future work requirements include experimental studies to investigate the likely impact of changing ocean pH, expanded monitoring of pCO_2, and other chemical indicators of the carbonate system state.

Climate Information Needs

U.S. AMLR currently is working to develop a structure to ensure monitoring of ocean pH, and dissolved inorganic carbon can be integrated into the US AMLR programs sampling scheme. We collaborate with researchers at PMEL, and this collaboration needs to be enhanced.

Where the NOAA climate program develops indicators, products or models reflecting the carbonate system of the ocean, U.S. AMLR would use such data in interpreting biological data collected within South Shetland Islands region. This would help U.S. AMLR to properly structure future data collection and interpretation of this important issue.

Resource Needs

The U.S. AMLR Program consists of 9 FTEs and 1 NOAA Corp Rotational officer. The Program maintains two field camps in the South Shetland Islands, and conducts oceanographic surveys during austral summer. Program PI's are in the field between 2 and 3.5 months each year. Thus, in order to address many of the research and management challenges regarding the impact of climate change, additional FTEs, instrumentation, and ship time will be required.

- Ship time: To address many of the questions regarding the monitoring of ocean resources, additional ship time will be required. The U.S. AMLR Program currently uses 70 days of ship time in the austral summer. A minimum of 30 additional sea days is required to develop programs to survey other areas, deploy and recover gear, and to extend the length of research activity at field camps. The lack of knowledge regarding the winter distributions of predators and krill will require additional winter ship time in ships with ice breaking capacity. Additionally, increasing the depth (to >2000m) to which oceanographic information will be collected could dramatically alter the allocation of ship time.

- Meteorological data: Increased support to develop self supporting automated weather stations is necessary.

- Ecosystem modeling: While current FTE composition is sufficient to provide support to contemporary modeling efforts, increased use of climate models and the development of decision support tools will require additional ecosystem modeling expertise. Moreover, inclusion of large-scale GCM output or modeling investigations will necessitate increases in the oceanographic component of the U.S. AMLR Program to validate the projections from these models.

- Over winter biological observations: Increased funding for the deployment of satellite instrumentation on fur seals, penguins, and southern elephant seals is necessary to quantify patterns of habitat use during the overwinter period. Current deployment levels are too low to statistically validate population level habitat preferences. Moreover, considerable development through the Advanced Survey Technologies Initiative or other funding is necessary to engineer small, light, and hydrodynamically neutral instruments for deployment on marine mammals and seabirds that can monitor the entire winter time period (8 months).

- Physiological observations: Resolving the importance of ocean acidification will require additional resources. In addition to chemists that can monitor the acidity of the ocean from current sampling locations, physiologists will be necessary to understand the likely impact of the pH changes on the physiology of calcium pathways in a variety of single and multicellular organisms. This will require the development of an experimental physiology group or partnership to investigate these issues.

References

Barrera-Oro, E. R., and E. R., Marschoff. 2007. Information on the status of fjord *Notothenia rossii*, *Gobionotothen gibberifrons* and *Notothenia coriiceps* in the lower South Shetland Islands derived from a long term monitoring program (1983-2006) at Potter Cove. CCAMLR Science. 14:83-87.

Barrera-Oro, E. R., E. R. Marschoff, and R. J. Casaux. 2000. Trends in relative abundance of fjord *Notothenia rossii*, *Gobionotothen gibberifrons* and *Notothenia coriiceps* at Potter Cove, South Shetland Islands, after the commercial fishing in the area. CCAMLR Science. 7: 43-52.

Biuw, M., L. Boehme, C. Guinet, M. Hindell, D. Costa, J.-B. Charrassin, F. Roquet, F. Bailleul, M. Meredith, S. Thorpe, Y. Tremblay, B. McDonald, Y.-H. Park, S. R. Rintoul, N. Bindoff, M. Goebel, D. Crocker, P. Lovell, J. Nicholson, F. Monks, and M. A. Fedak. 2007. Variations in behavior and condition of a Southern Ocean top predator in relation to *in situ* oceanographic conditions. Proceedings of the National Academy of Sciences 104: 13705-13710

Boveng, P. L., L. M. Hiruki, M. K. Schwartz, and J. L. Bengtson. 1998. Population growth of Antarctic fur seals: Limitation by a top predator, the leopard seal? Ecology 79: 2863-2877.

Conil, S., and C. G. Menendez. 2006. Climate fluctuation of the Weddell Sea and its surroundings in a transient climate change scenario. Climate Dynamics. 27: 83-99.

Detrich, H. W., C. D. Jones, S. Kim, A. W. North, A. Thurber, and M. Vacchi. 2005. Nesting behavior of the icefish *Chaenocephalus aceratus* at Bouvetoya Island, Southern Ocean. Polar Biology. 28: 828-832.

Garrison, D. L. 1991. Antarctic sea ice biota. Amer. Zool. 31: 17-33.

Gille, S. T. 2002. Warming of the Southern Ocean since the 1950s. Science. 295: 1275-1277.

Goebel, M .E., B. I. McDonald, R. G. Haner, D. J. Krause, S. Seganti, J. D. Lipsky, J. Van Dommelen, and R. S. Holt. 2006a. Pinniped research at Cape Shirreff, Livingston Island, Antarctica, 2005/06. In: United States Antarctic Marine Living Resources Program 2001/02 Field Season Report. Ed. J.D. Lipsky. NOAA Tech. Memo. SWFSC-350. Southwest Fisheries Science Center, La Jolla, CA 92037.

Goebel, M. E., B. I. McDonald, J. D. Lipsky, V. Vallejos, R. A. Vargas, O. Blank, D. P. Costa, and N. J. Gales. 2006b. A life table for female Antarctic fur seals breeding at Cape Shirreff, Livingston Island. CCAMLR Working Group on Ecosystem Monitoring and Management. Walvis Bay, Namibia.

Hewitt, R.P. D.A. Demer, J.H. Emery**.** 2003. An 8-year cycle in krill biomass density inferred from acoustic surveys conducted in the vicinity of the South Shetland Islands during the austral summers of 1991-1992 and 2001-2002. Aquat. Liv. Res. 16: 205-213.

Hinke J, K. Salwicka, S. G. Trivelpiece, G. Watters, and W. Z. Trivelpiece. 2008. Comparison of long-term trends in abundance, recruitment, and reproductive success of five populations of *Pygoscelis* penguins in the South Shetland Islands, Antarctica. Oecologia. 153: 845-855.

Jones, C. D., K.-H. Kock, and E. Balguerias. 2000. Changes in biomass of eight species of finfish around the South Orkney Islands (Subarea 48.2) from three bottom trawl surveys. CCAMLR Science 7: 53-74.

Klinck, J. M. 1998. Heat and salt changes on the continental shelf west of the Antarctic Peninsula between January ’93 and January ’94. J. Geophys. Res. 103: 7617-7636.

Kock, K.-H., and C. D. Jones. 2005. Fish Stocks in the Southern Scotia Arc Region – A Review and Prospects for Future Research. Reviews in Fishery Science. 13: 75–108, 2005.

Loeb, V., V. Siegel, O. Holm-Hansen, R. Hewitt, W. R. Fraser, W. Z. Trivelpiece, and S. G. Trivelpiece. 1997. Effects of sea-ice extent and krill or salp dominance on the Antarctic food web. Nature. 387897-900.

Meredith, M. P., P. L. Woodworth, C. W. Hughes, and V. Stepanov. 2004. Changes in the ocean transport through Drake Passage during the 1980s and 1990s, forced by changes in the Southern Annular Mode. Geophys. Res. Let. 31: 21305-21310.

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.

Sprintall, J. Seasonal to interannual upper-ocean variability in the Drake Passage. J. Mar. Sci. 61: 27-57.

Trivelpiece, W. Z, S. Buckelew, C. Reiss, and S. G. Trivelpiece. 2007. The winter distributions of chinstrap penguins from two breeding sites in the South Shetland Islands of Antarctica. Polar Biology. 30: 1231-1237.

Turner, J., S. R. Colwell, G. J. Marshall, T. A. Lachlan-Cope, A. M. Carleton, P. D. Jones, V. Lagun, P. A. Reid, and S. Iagovkina. 2005. Antarctic Climate change during the last 50 years. Int. J. Climatology. 25: 279-294.

Vaughan, D. G., G. J. Marshall, W. M. Connolley, C. L. Parkinson, R. Mulvaney, D. A. Hodgson, J. C. King, C. J. Pudsey, and J. Turner. 2003. Recent rapid regional climate change on the Antarctic Peninsula. Clim. Change. 60: 243-274.

Zwally, H. J., J. C. Comiso, C. L. Parkinson, D. J. Cavalieri, and P. Gloerson. 2002. Variability in Antarctic sea ice 1979-1998. J. Geophys. Res. 107: 3041-3059.

Appendix A - List of Acronyms

ACC - Antarctic Circumpolar Current
AFSC - Alaska Fisheries Science Center
AMO - Atlantic Multidecadal Oscillation
AOML – Atlantic Oceanographic and Meteorological Laboratory
CalCOFI – California Coordinated Oceanic Fisheries Investigations
CCAMLR - Convention for the Conservation of Antarctic Marine Living Resources
CeNCOOS - Central and Northern California Ocean Observing System
CCE - California Current Ecosystem
CODAR – Coastal Ocean Dynamics Applications Radar
COOS – Coastal Ocean Observing System
CPC – Climate Prediction Center
CRED - Coral Reef Ecosystem Division
CREWS - Coral Reef Early Warning System
CTD – Conductivity, Temperature, Depth
DSL - Deep Scattering Layer
EFH - Essential Fish Habitat
EKE – Eddy Kinetic Energy
EMAX - Energy Modeling and Analysis Exercise
ENSO - El Niño-Southern Oscillation
ESRL – Earth System Research Laboratory
ETP – Eastern Tropical Pacific
FADs - Fish Aggregating Devices
FATE – Fisheries And The Environment
FMP – Fisheries Management Plan
FOCI - Fisheries-Oceanography Coordinated Investigations
FP – fibropapilloma
GCM - Global Circulation Model
GFDL – Geophysical Fluid Dynamics Laboratory
GLOBEC – Global Ocean Ecosystems Dynamics
GPS – Global Positioning Satellite
HMS – Highly Migratory Species
IEA - Integrated Ecosystem Assessment
IOOS – Integrated Ocean Observing System
IPCC - Intergovernmental Panel on Climate Change
LIDAR - Light Detection and Ranging
LME – Large Marine Ecosystem
LOSI – Loss Of Sea Ice
MACOORA - Mid-Atlantic Coastal Ocean Observing Regional Association
MARMAP – Marine Resources Monitoring, Assessment and Prediction
MPA – Marine Protected Area
NANOOS - Northwest Association of Networked Ocean Observing Systems
NAO - North Atlantic Oscillation
NASA – National Aeronautics and Space Administration
NCDC – National Climatic Data Center

NCEP – National Centers for Environmental Prediction
NEFSC - Northeast Fisheries Science Center
NERACOOS - Northeastern Regional Association of Coastal Ocean Observing Systems
NGO – Non-Governmental Organization
NMFS – National Marine Fisheries Service
NODC – National Oceanographic Data Center
NOAA – National Oceanic and Atmospheric Administration
NPCREP – North Pacific Climate Regimes and Ecosystem Productivity
NPI - North Pacific Index
NPRB – North Pacific Research Board
NPTZ - North Pacific Transition Zone
NPZ – Nutrient-Phytoplankton-Zooplankton
NSF – National Science Foundation
NWFSC - Northwest Fisheries Science Center
NWHI – Northwest Hawaiian Islands
NWS – National Weather Service
OA – Ocean Acidification
OAR – Office of Oceanic and Atmospheric Research
PaCOOS – Pacific Coastal Ocean Observing System
PAR – Phytosynthetically Active Radiation
PFMC – Pacific Fishery Management Council
PIFSC – Pacific Islands Fishery Science Center
PDO - Pacific Decadal Oscillation
PMEL – Pacific Marine Environmental Laboratory
psu – practical salinity units
RAs - Regional Associations
ROMS - Regional Ocean Circulation Models
SAFE - Stock Assessment and Fishery Evaluation
SCOOS - Southern California Ocean Observing System
SEFSC – Southeast Fisheries Science Center
SOI – Southern Oscillation Index
SSI - South Shetland Islands
SST – Sea Surface Temperature
STSSN - Sea Turtle Stranding and Salvage Network
SWFSC – Southwest Fisheries Science Center
TOPP - Tagging of Pacific Pelagics
TZCF - Transition Zone Chlorophyll Front
UCDW - Upper Circumpolar Deep Water
U.S. AMLR - U.S. Antarctic Marine Living Resources program
YOY – Young of Year