A Component of the U.S. Global Change Research Program

Report on Climate Change and Carrying Capacity of the North Pacific Ecosystem

U.S. Global Ocean Ecosystems Dynamics

Report Number 15

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U.S. GLOBEC

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This is a report of the U.S. GLOBEC Workshop on the Climate Change and Carrying Capacity of the North Pacific Ecosystem held at the Batelle Conference Center in Seattle, WA, USA, from 19-20 April 1995. Anne Hollowed and Art Kendall co-chaired the workshop. The workshop report was edited by Anne Hollowed. The following people made a significant contribution by making a presentation at the meeting, preparing text for the background document used in preparation for the meeting, or in preparing text for the workshop report.

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Table of Contents

EXECUTIVE SUMMARY

Introduction

This report summarizes discussions and recommendations for a future research program on Climate Change and the Carrying Capacity (CCCC) of the North Pacific. The material presented in this report is the product of a U.S. GLOBEC workshop held at the Battelle Conference Center in Seattle, Washington, in April 1995. The need for the workshop stemmed from the development of a Science Plan for a international coordinated research effort on Climate Change and the Carrying Capacity, which was approved by the North Pacific Marine Science Organization (PICES), in October 1994. In response to the PICES Science Plan, the U.S. GLOBEC Scientific Steering Committee agreed to support a community-wide workshop to explore issues of the oceanic and coastal domains of the Subarctic Pacific and the Bering Sea relevant to U.S. GLOBEC.

The Research Program

The central scientific issues to be addressed by the PICES / GLOBEC CCCC program are:

1. Physical forcing: What are the characteristics of climate variability; can interdecadal patterns be identified; how and when do they arise?

2. Lower trophic level response: How do primary and secondary producers respond in productivity, and in species and size composition, to climate variability in different ecosystems of the Subarctic Pacific?

3. Higher trophic level response: How do life history patterns, distributions, vital rates, and population dynamics of higher trophic level species respond directly and indirectly to climate variability?

4. Ecosystem interactions: How are Subarctic Pacific ecosystems structured? Do higher trophic levels respond to climate variability solely as a consequence of bottom-up forcing? Are there significant intra-trophic level and top-down effects on lower trophic level production and on energy transfer efficiencies?

Recommendations for Initial Activities:

In this document we highlight four broad research questions that focus on physical forcing, lower trophic level response, higher trophic level response and ecosystem interactions. Efforts to define sub–sets of research projects that would advance our knowledge of the North Pacific and Bering Sea system and provide insight to these research questions were identified in each of the regional breakout sessions. Examples of potential projects that could be conducted to address the sub–set of questions were advanced for each of the three study regions (the oceanic and coastal domains of the Subarctic Pacific, and the Bering Sea). These questions could form the basis of Announcements of Opportunity for research at a later date. Key research activities related to these issues included retrospective analyses, development of models, process studies, development of observational systems (monitoring), and data management. If funds could be secured to support this program, the first AO would probably emphasize retrospective, modeling, and monitoring studies.

Products:

Contributions of a U.S. GLOBEC CCCC program might include:

- The development and/or refinement of coupled bio–physical models that could be used to examine hypotheses regarding potential impacts of climate variability on marine ecosystems.

- Improved knowledge of the impact of climate variability on marine ecosystems of the North Pacific. Specifically, the program could elucidate mechanisms controlling marine populations including commercially important fish species and provide quantitative information that would improve the assessment, conservation and management of our nations valuable marine resources.

- Data sets will be assembled during the program that will provide the basis of future research activities in the region.

- The program will advance our ability to make predictions on the future composition of marine communities which could be utilized in simulation models to assess the impact of human activities in the region.

- Studies of how physical forcing couples to the ecosystem will help scientists to anticipate future ecosystem changes, no matter how the climate evolves. Short–term (seasonal) to long–term (decadal) climate variations seem to impact the biological environment. The interdependence of these climate fluctuations and the nature of the biological responses could serve as proxies for prediction of some aspects of future long–term changes.

INTRODUCTION

U.S. GLOBEC Program

The U.S. **GLOB**al Ocean **EC**osystems Dynamics (U.S. GLOBEC) program has a goal of understanding how physical processes influence marine ecosystem dynamics in order to predict the response of the ecosystem and the stability of its food web to climate change. The program proposes to accomplish this goal by (1) undertaking field studies in several ocean ecosystem types, (2) developing models of the biological and physical systems, particularly focusing on the mechanistic coupling of the biology and physics, (3) developing improved technologies to sample the ocean environment, but more importantly encouraging wider application of existing, underutilized technologies to sample the ocean, and (4) examining or re-examining existing data sets in a retrospective fashion, to both guide future sampling programs and to document past variability due to both natural and anthropogenic factors.

U.S. GLOBEC's Initial Science Plan (U.S. GLOBEC, 1991a) identified specific criteria for the selection of field study sites. Those criteria include: a demonstrable linkage of the field program to climate change; a focus on secondary producers in the marine ecosystem, including zooplankton, fish and benthos; demographically and/or geographically distinct populations are to be the focus, since one must be able to define a population in order to study that population's fluctuations; the research must ultimately lead to better understanding of how the population dynamics of the target species are related to physical processes, many of which may be modified by climate change; ideally, U.S. GLOBEC study sites would have sufficient historical data on both physics and biology to provide a longer term context for field studies of 5-7 year duration, and to assist in planning the research and verifying models of the system; and finally, to the extent possible, U.S. GLOBEC field studies should be integrated both with other global change programs, and with international collaborators.

The Initial Science Plan identified several ecosystems that satisfied most of the criteria provided above: (1) Georges Bank, (2) a Pacific Basin study; (3) an Arabian Sea study; and, (4) a Southern Ocean study. The Georges Bank study was started in 1992. U.S. GLOBEC has funded planning meetings and developed, or assisted in the development, of GLOBEC science plans for studies in the Arabian Sea, the Southern Ocean, and the California Current.

U.S. GLOBEC's intent in all its field studies is to begin by funding modeling and retrospective projects before committing to large, and expensive, field programs. This plan was followed successfully in the Georges Bank program. In the spring of 1995 we began our Southern Ocean program similarly, by soliciting modeling proposals of relevance to Southern Ocean ecosystems. We expect that GLOBEC field studies in the Southern Ocean will commence several years from now.

The Initial Science Plan identified several regions in the eastern North Pacific that might be suitable sites for intensive U.S. GLOBEC field studies: (1) an eastern boundary current ecosystem as typified by the California Current; (2) a buoyancy-driven coastal current ecosystem as typified by the Pacific Northwest and Alaska continental margin, including the

Bering Sea; and, (3) an open ocean ecosystem as typified by the Alaska Gyre. Of these, planning for a program in the California Current is advanced, with several meetings leading to the production of a report on the relation between climate and the ecosystem (U.S. GLOBEC, 1992) and a Science Plan for the California Current (U.S. GLOBEC, 1994). The California Current Science Plan identifies four major questions that GLOBEC should address. They relate to (1) seasonal-to-interannual variability in biological responses, (2) decadal and longer variability in biological responses, (3) mesoscale variability in biological responses, and (4) latitudinal gradients in biological responses. Details of the proposed U.S. GLOBEC California Current program can be obtained from the U.S. GLOBEC office in Berkeley, CA or from the World-Wide Web at URL:

http://www.usglobec.berkeley.edu/usglobec/globec.homepage.html

PICES GLOBEC CCCC Program

History of PICES-GLOBEC Climate Change and Carrying Capacity (CCCC) Initiative:

PICES is an intergovernmental organization established in 1992 to promote and coordinate marine scientific research in the temperate and subarctic region of the North Pacific and its adjacent seas. PICES members are Canada, China, Japan, Korea, Russia, and the United States. At its First Annual Meeting in 1992 PICES created Working Group 3, on Dynamics of Small Pelagics in Coastal Ecosystems, and Working Group 6 (WG6), on the Subarctic Gyre (WG3).

Terms of reference for WG3 included:

- Develop a program for a comparative study of the population dynamics and productivity of small pelagics (focusing on herring, sardine, anchovy, and mackerel) in the coastal ecosystems along the western and eastern continental margins of the North Pacific.

Terms of reference of WG6 included:

- Review existing information on the carrying capacity for salmon and other nektonic species in the subarctic, and what is known about variations in the carrying capacity of this region in response to climate change. Advise on how changes in carrying capacity could be quantified.

- Review existing level of knowledge of the processes affecting primary and secondary production in this region and identify information gaps. Advise on how these gaps could be studied.

- Identify key scientific questions, and propose collaborative programs which can be conducted to advance knowledge and test major hypotheses.

- Determine relationships to GLOBEC. Advise which PICES and GLOBEC objectives could be linked.

Reports of the two Working Groups are contained in PICES Scientific Report No. 1 (PICES, 1993) which includes WG6's review of the Subarctic Pacific, with summaries of its physics and biology (phytoplankton, zooplankton, and fish). Recommendations to the Science Board included two that are particularly relevant to the current workshop:

> – PICES should support GLOBEC activities in the North Pacific region, especially those directed towards understanding the physical and biological oceanographic linkages to long term variations in zooplankton and fish populations.
>
> – A scientific workshop should be organized in 1994 on a "PICES-GLOBEC Program for the North Pacific Ocean. The purpose would be to develop and plan further collaborative research programs between PICES and International GLOBEC for the North Pacific Ocean.

The PICES Second Annual Meeting (fall 1993) authorized preparation of a draft Science Plan for what was called the PICES GLOBEC-International Program on Climate Change and Carrying Capacity (CCCC). The Plan was then discussed at a workshop and approved at the PICES Third Annual Meeting (fall 1994) where it was agreed to establish a Scientific Steering Committee (now called Implementation Group) to initiate development of an implementation plan. An Executive Committee of that Group met in May 1995 to prepare a draft for review and revision during the summer (a preliminary draft was available at the Seattle Workshop in April 1995).

Central Questions

The CCCC Science Plan emphasizes that research activities are anticipated on two spatial scales:

> 1. Basin-scale studies to determine how plankton productivity and the carrying capacity for high–trophic level pelagic carnivores in the North Pacific change in response to climate variations.
>
> 2. Regional scale ecosystem studies comparing how variations in ocean climate affect species dominance and fish populations at the coastal margins of the Pacific Rim.

The Key Scientific Questions postulated in the Science Plan have since been consolidated into the set of so-called Central Scientific Issues presented on page 1. Key research activities related to these issues will include retrospective analyses, development of models, process studies, development of observational systems, and data management. The next steps in developing the CCCC implementation plan on the regional scale are expected to include efforts to design the proposed comparison of ecosystem properties and responses to climate variability in cooperation with national GLOBEC programs. On the basin scale, a more comprehensive effort to develop an international cooperative program will be required.

PROGRAM RATIONALE

The North Pacific is an attractive site for a U.S. GLOBEC program for several reasons. Many commercial industries in the Pacific Northwest and Alaska are heavily dependent on natural resources. For example, approximately half of the total U.S. fisheries catch is removed from waters off the coast of Alaska (Anon. 1993). Many studies have shown a strong connection between climatic variables and indices of fish abundance and distribution in the North Pacific (see collection of papers Beamish 1995, and Beamish and McFarlane 1989). These strong responses to climatic change translate into direct impacts on the efficiency and sustainability of the region's fishing industry. Elucidation of long term influences of climate change on these natural resources could have important benefits to the nation by improving our knowledge of functional relationships between climatic conditions and biological production that would allow for the development of long range plans for resource conservation and management.

The North Pacific is the location of one of the major storm tracks in the northern hemisphere. Simulation models suggest that the southern side of the Arctic front will be the region of greatest alteration due to global climate change. The storm track responds to two global teleconnection patterns, 1) the West Pacific oscillation that influences the location of storm generation and 2) the Pacific-North American (PNA) pattern that influences the track of storms across the Subarctic Pacific. The PNA pattern is often considered the major mode of planetary variability of the atmosphere. We can hypothesize the shift in storm frequency and track due to climate change, and its potential impact on the physical environment (see Climate Change scenarios). Any systematic shifts that occur will be modulated by the large natural variability that exists on time scales from seasonal to millennia. This variability has a profound impact on circulation, mixed layer depths and the extent of ice coverage, all of which influence the rich biological resources of the Subarctic Pacific and Bering Sea.

At the present time, we are poised to take advantage of newly developed tools that will enable us to address the questions of carrying capacity of the Subarctic Pacific. These include measurement technologies and complex computer models. The vast time-space scope of the environmental questions requires application of technologies such as remote sensing via aircraft and satellite, shipboard data acquisition systems such as those employing acoustic sampling of currents and biota, and moored platforms to collect high resolution time series of biological and physical observations. Advances in computer technology now permit using large-scale models that assimilate field observations and integrate biological and physical processes. Even over remote regions like the North Pacific Ocean, the atmosphere can be monitored and modeled operationally well enough that the large–scale forcing of the ocean can be specified. For example, The TOGA-TAO array in the South Pacific will provide excellent coverage of the development of El Niño Southern Oscillation events, which can be related to processes in the North Pacific. In addition, once underway the ATOC (Acoustic Thermography of the Ocean Climate) program will provide ocean basin scale information on temperature variations and the heat budget of the North Pacific Ocean.

A U.S. GLOBEC program in the North Pacific would benefit from parallel development of complementary research programs of other nations through the PICES–GLOBEC Climate Change and Carrying Capacity program. International cooperation on a common research program will inevitably enhance our national research efforts. In the case of coastal programs, Japanese and Russian studies in the Bering Sea, and Canadian research off British Columbia will augment U.S. investigations of ecosystem responses to climate variability.

U.S. GLOBEC research programs in the North Pacific would complement proposed research for the California Current (U.S. GLOBEC 1994). Coordination with the California Current program is highly desirable because large scale forcing for both regions could be modeled simultaneously.

Linkages to Other Field Programs

The North Pacific is a desirable region for U.S. GLOBEC research efforts partially because of the potential for coordination with five existing process oriented programs. A short description of each of these programs follows.

1. Fisheries Oceanography Coordinated Investigations (FOCI): FOCI focuses research on biological and physical processes that influence survival of walleye pollock (*Theragra chalcogramma*). FOCI is comprised of scientists at the Pacific Marine Environmental Laboratory, the Alaska Fisheries Science Center, and several other institutions who have been studying both the biotic and abiotic environment, including processes within larval patches through integrated field, laboratory and modeling studies. The original focus of FOCI was recruitment to the pollock population spawning in Shelikof Strait.

2. Bering Sea FOCI: Bering Sea FOCI, a component of NOAA's Coastal Ocean Program has been studying production of walleye pollock in the Bering Sea since 1991. The Bering Sea FOCI program is a six year research program that ends in 1996. The Bering Sea FOCI program has two main thrusts: investigation of stock structure of pollock in the Bering Sea, and investigation of recruitment of walleye pollock in the southeast portion of the Bering sea, where significant spawning takes place.

3. Southeast Bering Sea Carrying Capacity (SEBSCC): SEBSCC is a new regional study funded through NOAA's Coastal Ocean Program. Southeast Bering Sea Carrying Capacity will focus resources during each of the next five years to improve our understanding of the Bering Sea ecosystem. This program begins in 1996 and will continue through 2001.

4. Exxon Valdez Oil Spill Trustees (EVOS): The EVOS Trustees support research programs that will guide the development of an integrated science plan for restoration of species potentially injured by oil spills in Prince William Sound, Gulf of Alaska. These programs include the Sound Ecosystem Assessment (SEA) program, and the Apex Predator Ecosystem Experiment (APEX) . SEA is an interdisciplinary, multi–component program designed to understand factors constraining pink salmon and herring production in Prince William Sound, Alaska.

5. NMFS Ocean Carrying Capacity studies (OCC). The NMFS Auke Bay laboratory initiated the OCC study on Pacific salmon in the Gulf of Alaska in 1995. The OCC study is focused around cooperative Canada-U.S. research surveys on the marine life history of Pacific salmonids and will include studies of: age-at-maturity, modeling and diet studies, and retrospective studies of salmon growth. These process oriented research programs will provide: a) estimates of many of the critical biological parameters required to develop a coupled bio-physical model, and b) spatially explicit physical models for the region.

Canadian scientists also have a long history of fisheries oceanographic research. The Canadian La Perouse program provides a continuous time series of biological and physical oceanographic conditions off the outer coast of Vancouver Island since 1985.

The FOCI and the Canadian La Perouse Programs are among the most mature fisheries oceanography programs in the world. Few fisheries oceanography programs have been able to maintain continuous coordinated research for more than a decade. The findings from these two programs provide many of the critical parameters for the development of larger scale ecosystem models necessary to study climate change and carrying capacity of the North Pacific and Bering Sea. For example, the FOCI program has enumerated abundance trends at various life stages of early development; examined processes affecting life stages; mapped horizontal, vertical, and temporal distributions; described the oceanic and atmospheric environment; developed coupled bio–physical models of the Gulf of Alaska, and developed techniques to examine recruitment–process hypotheses.

Regional Boundaries

The geographic boundary between the coastal regions of the Gulf of Alaska and the open subarctic has not been defined by the PICES/CCCC/SSC. The following working definition is offered by GLOBEC:

1. The open subarctic region will include Pacific Waters north of the position of the isohaline of 34.0 psu in the upper mixed layer with the exception of the coastal regions over the continental shelf and slope (to depths of 1000 m).

2. The Bering Sea includes all oceanic waters north of the Aleutian Islands but south of the Chukchi Sea.

3. The coastal regions of the Subarctic Pacific will include all waters over the continental shelf and slope to depths of 1000 m. This coastal region will include areas south of the Aleutian Islands to the western boundary of U.S. waters at 173°E.

Some species, such as salmon, undertake seasonal migrations that cross both the coastal Gulf of Alaska and the open subarctic. It is recognized that processes in the subarctic gyre would be extended where necessary to include all areas and species of the North Pacific and marginal seas which currently are known to, or potentially could, significantly affect the physics, chemistry or biology of the subarctic gyre.

WORKSHOP STRUCTURE AND SUMMARY

Workshop Structure

The workshop began with background briefings on U.S. GLOBEC planning and research activities, and an introduction to the PICES Climate Change and Carrying Capacity Science Plan. Participants were then divided into six multi–disciplinary breakout groups. These six breakout topics covered issues that were relevant to the development of a research plan designed to address the impact of climate variability on biological systems: climate change, regime shifts, carrying capacity, modeling, technology, spatial and temporal scales. The following day, participants were divided into groups to discuss specific recommendations for future research in three geographic regions: Gulf of Alaska, oceanic subarctic, and the Bering Sea. The following summaries provide a synopsis of the discussions and recommendations made in each of the breakout sessions. More detailed accounts of group discussions are found in the breakout session chapters.

Breakout Session 1. Climate Change: What are the likely scenarios for climate change in the North Pacific and how would they influence the ecosystem?

This breakout session was devoted to discussion of the potential impact of climate change possibly caused by increased CO_2 and other greenhouse gases from anthropogenic sources. Climate change would influence North Pacific ecosystems primarily through four physical factors: mixed layer depth (MLD), volume and location of marine habitat, sea ice, and river outflows. MLD is strongly correlated with biological productivity over the entire North Pacific, but the response of MLD to climate change is liable to be different in the three main regions. Changes in marine habitat, thus the zoogeographic distribution of marine species, are expected to accompany ocean warming, with particular impacts on species at the edge of their ranges. Sea ice is foreseen to decrease both in space and seasonal duration, with effects on the Bering Sea's primary productivity and distribution of many marine fish, sea birds and mammals. The overall magnitude and seasonal cycle of river flows may change significantly, with implications for coastal currents and freshwater habitats for salmon.

Breakout Session 2. Regime shifts and decadal shifts: can they be detected, what is their impact, are they predictable?

There is compelling evidence of interdecadal changes in the physical environment of the North Pacific and Bering Sea. The most recent shift occurred in the late 1970's. These changes appear to be linked to large scale shifts in atmospheric processes. Marine organisms seem to respond to these decadal scale changes in the physical environment. The group acknowledged that additional research is required to improve our understanding of the mechanisms underlying the response of marine organisms to shifts in physical conditions. North Pacific basin modeling shows promise in simulating and explaining decadal fluctuations of the ocean over coarse scales. Regional and mesoscale oceanographic models exist for the Gulf of Alaska and need to be developed for other regions. Several physical and biological variables were identified that could be used as diagnostic indicators of regime shifts.

Breakout Session 3: What is carrying capacity?

This breakout group discussed the concept of carrying capacity and methods to measure carrying capacity. The group adopted the following definition of carrying capacity:

> Carrying capacity is a measure of the biomass of a population that can be supported by the ecosystem. The carrying capacity changes over time with the abundance of predators and supply of food. The food supply is a function of the productivity of the prey populations and competition for that food from other predators. Changes in the biotic environment affect the distributions and productivity of all populations involved.

The group discussed several indices of carrying capacity that could be used to assess relative changes in the status of a population. The group noted that size spectrum theory, which relates rates of productivity to the size class of organisms in the ecosystem, is a potentially valuable conceptual framework for examining carrying capacity questions. Measurements of climate change effects on the carrying capacity might be examined using fishing experiments to examine the impact of the removal or exclusion of a particular component of the ecosystem.

Breakout Session 4: What is required to model the impact of climate change on the carrying capacity of the region?

Participants discussed a variety of modeling approaches and suggested that different types of models could be beneficially nested: spatially, temporally and trophically. Many physical models of the North Pacific and Bering Sea already exist and could be utilized in the U.S. GLOBEC program. While the formulation of governing equations and choice of parameters for bio–physical models is difficult, reasonable choices can be made. Encouraging results have been obtained from the application of coupled bio–physical models in other areas of the world (such as the North Atlantic).

Breakout Session 5: What are the technological impediments to measuring the effects of climate change on the carrying capacity?

This group recognized that climate change by definition is a large scale, long term process and will require ample measurements collected over a large geographical area for a long duration. They recognized that a successful program will require that study sites are selected at key or pulse points where the variance is minimized and the effects of climate change on carrying capacity are indicative of large scale change. A variety of technical issues were discussed and the disadvantages and advantages of each were identified. The group encouraged efforts to measure sea-surface salinity from satellites to map the large-scale distribution of this variable which is dynamically more important than temperature in the Gulf of Alaska and Bering Sea due to large freshwater inputs. They also noted that deep ocean currents could be monitored using electromagnetic observations from submarine telephone cables and identified the Kamchatka Current and Alaskan Stream as pulse points. Finally they noted the need for research on noncommercial species such as jellyfish or forage fish. These species may play a critical role in determining the carrying capacity of oceanic systems.

Breakout Session 6: What are the spatial and temporal scales required to resolve questions concerning climate change and the carrying capacity?

This group concluded that the spatial scale of climate forcing is large, basin scale at least. The group noted that while considerable attention has been devoted to interannual variations, decadal and longer time scales may be more important for resolving issues of climate forcing and its impact on marine ecosystems. Participants acknowledged that the response time to climate change differs between species. Criteria for selecting specific time and space scales for a future U.S. GLOBEC study must include: 1) concentration of important variability, 2) relationship to plausible mechanisms of interaction, 3) relationship to applied problems.

Coastal Gulf of Alaska Breakout Session

Participants in this Breakout Session were asked to define a subset of research questions that should be investigated to advance our understanding of the impact of climate change on: physical forcing, lower trophic level species, and higher trophic level species. Forcing questions focused on four forcing factors: atmospheric forcing, interactions between the Alaska Stream and Alaska Coastal Currents, the influence of bottom topography on coastal circulation, and tidal influence on nutrient flux. These four large scale factors influence important physical processes such as: mixed layer depth, mixed layer temperature, retention times (eddies), turbidity, and cross shelf transport. Research to describe the functional relationship between large scale forcing and local conditions will be required. Lower trophic level questions focused on five research topics including: transport influences on the composition and production of plankton communities, the role of grazing and predation on the structure of plankton communities, trophic phasing, climate change effects on over wintering plankton communities, and freshwater influences on plankton communities. Several potential research topics relevant to higher trophic level species were discussed including efforts to identify climate change effects : a) the spatial distribution of predators, b) prey abundance, c) species composition of fish communities, and d) seasonality of resources to apex consumers.

Research activities that might be undertaken to answer these questions included retrospective studies, monitoring studies, process oriented research and modeling. In the Gulf of Alaska many physical and biological datasets exist that could be used for retrospective analyses. Likewise, many potentially valuable monitoring platforms in the Gulf of Alaska were identified. Bio–physical models have been developed for British Columbia, Prince William Sound and Shelikof Strait. Efforts to nest regional models of Shelikof Strait (NOAA's FOCI program), Prince William Sound (Exxon Valdez Oil Spill Trustees, SEA program), and Southeast Alaska (APRISE, Canada's La Perouse program) into a large-scale bio–physical model of the Gulf was recommended. A broad-scale biological model of the Gulf might include the following: phytoplankton and protozoa, euphausiids and copepods, jellyfish, salmon, herring, and pollock.

Oceanic Subarctic Breakout Session

This breakout group divided into three subgroups to discuss projects relevant to 1) physical forcing/lower trophic level response, 2) higher trophic level response, and 3) ecosystem interactions. The first group identified three projects for future study: a program to document changes in standing stocks of plankton, a project to distinguish the effects of iron, Ekman pumping, cloud variation, and other factors on primary production, and a test of the Chelton hypothesis on the split of the west wind drift as it nears North America. Five questions were identified for future research of higher trophic level responses. These questions focused on mechanisms responsible for sustained high biomass of higher trophic level species since 1976–77, identifying historical biomass levels, studies to examine the coherence between the eastern and western gyres, bio–physical interactions, and regulatory factors controlling the carrying capacity of salmon. The ecosystem sub–group identified four research topics: effects of Kuroshio/Oyashio currents on coastal ecosystems of Asia and the deflection of these currents into the eastern subarctic, effects of subarctic currents and ENSO events on the subarctic coastal ecosystem, effects of the transition zone on the subarctic ecosystem and the effect of deep water species on near surface ecosystems. Retrospective, monitoring studies, process oriented and modeling projects were identified to address each of the research topics.

Bering Sea Breakout Session

The Bering Sea breakout group began their discussions by acknowledging that Bering Sea is possibly the most productive of the northern high latitude seas. The group noted that a first order understanding of the Bering Sea has been obtained and that research programs should focus on studies aimed at elucidating the mechanisms linking environmental change to responses of the system. Four specific research topics were identified by the group:

1) what is the relation of the range of storm activity to the annual production budget and food web dynamics of the mixed layer?
2) What is the relation of the sea ice melt–back bloom to total annual production?
3) How does the nature of the spring bloom determine the partition of energy between the pelagic and benthic ecosystem components?
4) Will climate change alter habitat/domain volumes and how will this influence recruitment?

Retrospective, modeling, process oriented studies and monitoring activities designed to answer these four questions were identified.

OVERVIEW OF PHYSICAL OCEANOGRAPHIC FEATURES

The following description of the physical and biological features of the three study regions provides a setting for subsequent discussions of the linkages between climate variability and ecosystem response.

Physical Oceanographic Setting

Figure 1 shows the climatological mean circulation patterns of the Subarctic Pacific based on geostrophic flow (e.g., Reed, 1984: Reed et al., 1993), and direct current measurements (Stabeno and Reed, 1994: Schumacher and Kendall, 1995: Schumacher and Stabeno, in press). The values of velocity given are estimates of typical flow. In the swifter currents, peak speeds can be substantially larger than the values given.

Oceanic Domain

The swiftest flow exists in the Kuroshio Current, but peak speeds (>100 cm s^{-1}) in the Alaskan Stream and the Kamchatka Current (Stabeno and Reed, 1991, 1994) are at least half those off Japan. The Kuroshio Current extension retains appreciable speeds, and the mixture of this water with the Oyashio Current is the broad slow Subarctic Current. The Subarctic Current is affected more by wind drift than any other flow in this region. It has geostrophic speeds that are usually ~ 5 cm s^{-1}, but winds blow in the same direction and augment speeds, especially during winter (McNally et al., 1983). The Subarctic Current diverges off the west coast of North America near Vancouver Island. The southward flow is the California Current, while the remainder turns northward into the Gulf of Alaska. As this flow leaves the head of the Gulf, it deepens, narrows, and intensifies. This westward flow, known as the Alaskan Stream, continues along the Aleutian Islands, with the majority (above 2000 m) entering the Bering Sea through Near Strait (170^{o} E) (Figure 2). Although flow of Alaskan Stream water through both Amchitka and Amukta Pass is relatively small in volume, it strongly influences water properties and circulation in the eastern Bering Sea (Schumacher and Stabeno, 1994; Reed and Stabeno, 1994; Reed, 1995).

The Bering Slope Current (BSC; Kinder et al., 1975, 1986; Schumacher and Reed, 1992) has a transport of 3-5 x 10^{6} m^{3} s^{-1}, and contains Alaskan Stream water that flows through Amchitka and Amukta Passes and then eastward along the northern side of the Aleutian Islands. The BSC influences slope water properties (Schumacher and Stabeno, 1994; Reed and Stabeno, 1994) which flux onto the outer continental shelf. A subsurface temperature maximum is a characteristic of the southern Bering Sea. It is > 4°C when the Alaskan Stream flows northward through Amukta Pass (Schumacher and Reed, 1992). Eddies are a common feature in the southeastern Bering Sea; some are formed by flow through Amukta Pass (Schumacher and Stabeno, 1994).

The northwestward flow of the BSC (3-15 cm s^{-1}) along the eastern shelf break is concentrated in the upper 300 m (Schumacher and Reed, 1992: Muench and Schumacher, 1985). Although wind energy approximately doubles in winter, kinetic energy of the current fluctuations and the

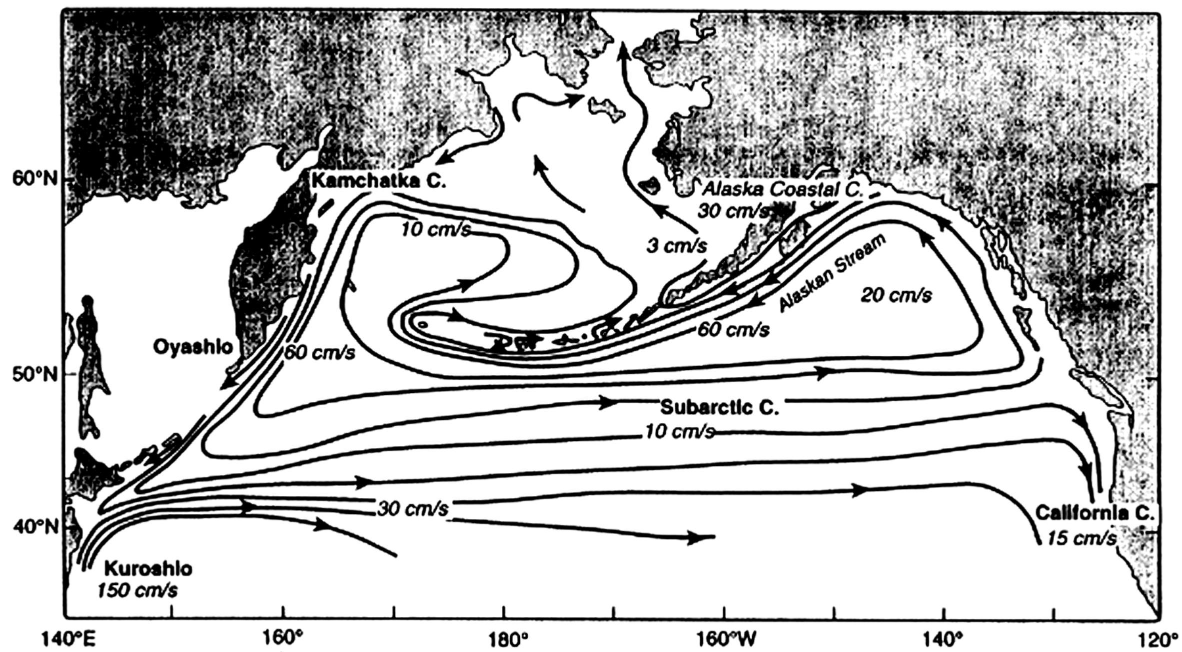

Figure 1. Estimates of the climatological mean surface circulation in the subarctic Pacific.

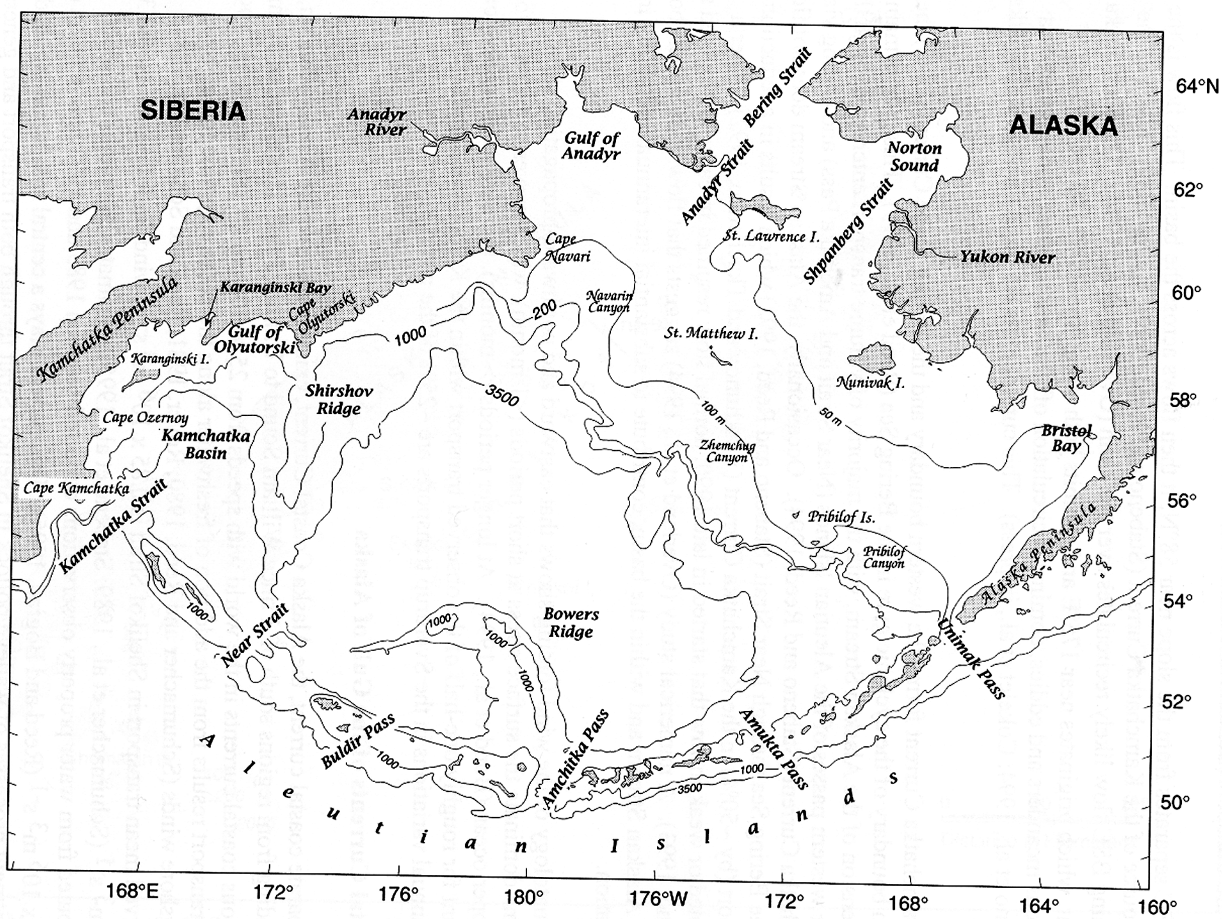

Figure 2. Depth contours and major topographic features of the Bering Sea and Aleutian Islands.

vector mean currents do not; only a small fraction of the current fluctuations measured here can be accounted for by the wind. Small (5-30 km) eddies with strong (20-30 cm s^{-1}) rotational speeds are features of the current regime. Estimates of salt fluxes indicate some significant shoreward transport (Schumacher and Reed, 1992).

The BSC separates from the slope near 58°N; it then flows across the basin. This flow is the main source of the Kamchatka Current (Stabeno and Reed, 1994: Khen, 1989). Much of the remaining BSC flow likely recirculates over the basin (Overland et al., 1994). The Kamchatka Current, which originates near 175°E and exhibits both strong speed (40-100 cm s^{-1}) and numerous meanders and eddies, dominates circulation off the western shelf of the Bering Sea (Stabeno et al., 1994: Cokelet et al., in press). This current exits the basin through Kamchatka Strait.

The Kamchatka Current forms the western boundary and the Bering Slope Current (BSC) the eastern boundary of the cyclonic gyre in the Bering Sea (Reed et al., 1993). This gyre is mainly an extension of the Alaskan Stream, with the majority of volume transport entering through the deeper western passes of the Aleutian Islands (Near Strait and Amchitka Pass) and exiting via the Kamchatka Current (Stabeno and Reed, 1994). Occasionally, the Alaskan Stream does not flow into the Bering Sea through Near Strait (Stabeno and Reed, 1992) which results in a reduction of transport (by ~50%) in the Kamchatka Current (Verkhunov and Tkachenko, 1992). After a disrupted or weak inflow that started in late 1990, normal flow resumed in early 1992 (Reed and Stabeno, 1993). A numerical study (Overland et al., 1994) suggests that flow instabilities, both in the Alaskan Stream and within the basin, contribute to substantial interannual variability in the circulation.

A climatology of the wind forcing shows that eastward and northward-propagating storm systems dominate the surface stress at short periods (<1 month), which serves principally to mix the upper ocean (Bond et al., 1994). At longer periods (> months), the wind-driven transports account for roughly one-half of the observed transport within the Kamchatka Current. The interannual variations in the Sverdrup transports are ~25% of the mean.

Coastal Currents of the Gulf of Alaska

A separate coastal current, the Alaska Coastal Current, exists inshore of the Alaskan Stream, extending from regions south of Prince William Sound to Unimak Pass. This is one of the most vigorous coastal currents in the world with speeds from 25 to 100 cm s^{-1} (Stabeno et al., 1995). The transport results from the addition of freshwater along the entire coastline forced by alongshore winds (Schumacher and Reed, 1980; Royer, 1981; Reed and Schumacher, 1981). The observed mean transport in Shelikof Strait is 0.85 x 10^6 m^3 s^{-1} ; wind forced pulses exceed 3.0 x 10^6 m^3 s^{-1} (Schumacher et al., 1989: Stabeno et al., 1995). Estimates of volume transport computed from water property observations collected between 1985 and 1992 have a mean of 0.66 x 10^6 m^3 s^{-1} (Reed and Bograd, 1995). This current plays a central role in survival and recruitment processes of walleye pollock in Shelikof Strait through both transport and generation of eddies (Schumacher and Kendall, 1995) (Figure 3).

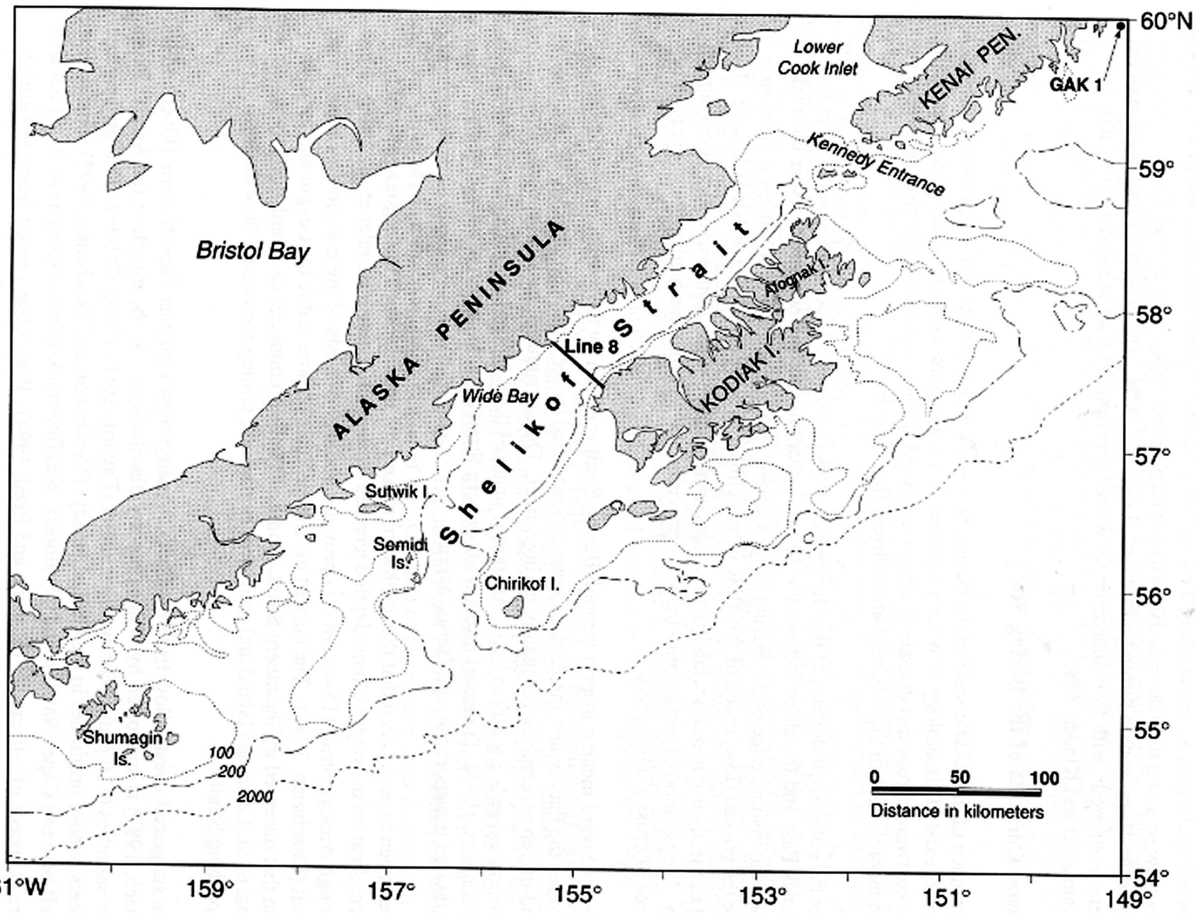

Figure 3. Depth contours and major topographic features of the western and central Gulf of Alaska.

The Alaska Coastal Current flows through Unimak Pass (~0.3 x 10^6 m^3 s^{-1}). Some turns eastward resulting in a current along the coastline (2-5 cm s^{-1}) with the remainder flowing toward the northwest along the 100-m isobath (Reed and Stabeno 1994). The coastal flow (< 3 cm s^{-1}) follows the 50-m isobath turning northward along near 58°N. The coastal current has a seasonal pattern in strength, with flow increasing in winter concomitant with increased storm activity (Schumacher and Kinder, 1983).

Coastal Currents of the Bering Sea

Over much of the middle shelf of the Bering Sea, weak and/or statistically insignificant mean currents exist. Climatology of water properties and Lagrangian measurements reveal a convoluted flow eastward across this domain (Stabeno and Reed, 1994). This advective feature has not yet been incorporated in the salt, heat and nutrient flux models.

Over the outer-shelf domain of the Bering Sea, flow (5-10 cm s^{-1}) containing water from both Unimak Pass and the slope follows the 100-m isobath toward the northwest. Near the shelf break, the inshore edge of the Bering Slope Current results in stronger (10-20 cm s^{-1}) currents. Like the coastal flow, much of this flow is baroclinic. While pulses of cross-shelf flow (5-10 cm s^{-1}) occur, their inherent variability precludes establishing a mean from existing moored current data. Propagation of eddies onto the shelf provides one possible mechanism for generation of pulses of cross-shelf current.

The northward mean transport through Bering Strait is driven by the surface height difference between the Pacific and the Arctic Ocean and modified by the wind. Strong (5 x 10^6 m^3 s^{-1}) wind-driven reversals occur mainly during winter. During summer, maximum northward transport exceeds 3 x 10^6 m^3 s^{-1}. An annual mean of 0.8 x 10^6 m^3 s^{-1} has been estimated (Coachman, 1993). Transport through Shpanberg Strait provides about one-third of the northward transport through Bering Strait.

It has been hypothesized that the northward mean flow over the shelf undergoes westward intensification as water column depth decreases from south to north (Kinder et al., 1986). Flow through Anadyr Strait (15-40 cm s^{-1}) provides about two-thirds of the transport through Bering Strait (Coachman, 1993). The current in Anadyr Strait is more stable in strength and location than that observed in Shpanberg Strait. Some of the flow continues eastward along the south coast of St. Lawrence Island and then turns northward, joining the coastal flow through Shpanberg Strait.

The suggested coastal flow from the Gulf of Anadyr westward past Cape Navarin (Overland and Roach, 1987) is supported by water property distributions. At the mouth of the Anadyr River, low salinities (~10 psu) occur during summer (Favorite et al., 1976). Dilute (<31.0 psu) surface waters, whose origin lies in the Gulf of Anadyr (Verkhunov and Tkachenko, 1992), exist over the shelf between Capes Navarin and Olyutorski. Satellite-tracked buoys (drogue at 40 m) transited here at speeds of ~40 cm s^{-1} (Stabeno and Reed, 1994). Buoy observations from the Gulf of Olyutorski show the strong (30-50 cm s^{-1}) flow of the Kamchatka Current over the slope, while more moderate (15-25 cm s^{-1}) speeds occur over the adjacent shelf. These observation suggest a coastal current over the western shelf.

In both the Gulf of Olyutorski and Karaginski Bay, quasi-stationary eddies exist, and similar features also occur in embayments along the Kamchatka coast (Stabeno et al., 1994; S. Gladyshev, unpublished manuscript). Satellite-tracked buoy trajectories substantiate such a feature in the bay centered at 54° N. Generation of these features likely results from meanders in the inshore flow interacting with topography and/or formation of saline lenses due to brine expulsion (Verkhunov, 1994).

Sea Ice

Oceanic conditions in the Bering Sea are influenced by the extent of ice cover (Figure 4). During extreme conditions, ice covers the entire eastern shelf, however interannual variability of coverage can be as great as 40% (Niebauer, 1988). The buoyancy flux from melting ice initiates both baroclinic transport along the marginal ice zone (~0.3 x 10^6 m^3 s^{-1}; Muench and Schumacher, 1985) and stratification. The ensuing ice edge bloom of phytoplankton accounts for between 10% and 65% of the total annual primary production (Niebauer et al., 1990). The nutrient-rich slope waters combine with summer solar radiation to create one of the world's most productive ecosystems (Walsh et al., 1989). Annual primary production varies from >200 gC m-2 over the southeastern shelf to >800 gC m^{-2} north of St. Lawrence Island. Over the western shelf, ice cover extends southwestward to Cape Kamchatka and seaward over the slope (Khen, 1989).

Ice production and cold bottom water exert an important influence on distributions of biota over both the western (Radchenko and Sobolevskiy, 1993) and eastern (Ohtani and Azumaya, 1995: Wyllie-Echeverria, 1995) shelves. The production of dense water has a marked impact on the halocline of the Arctic Ocean (Cavalieri and Martin, 1994), with water from the Anadyr and Anadyr Strait polynyas providing a substantial fraction of the total dense water. From 9 to 25 m of ice formation occurs depending on the location and duration of a given season (Cavalieri and Martin, 1994), but the average thickness of ice over most of the eastern shelf is only ~0.5 m (Coachman, 1986).

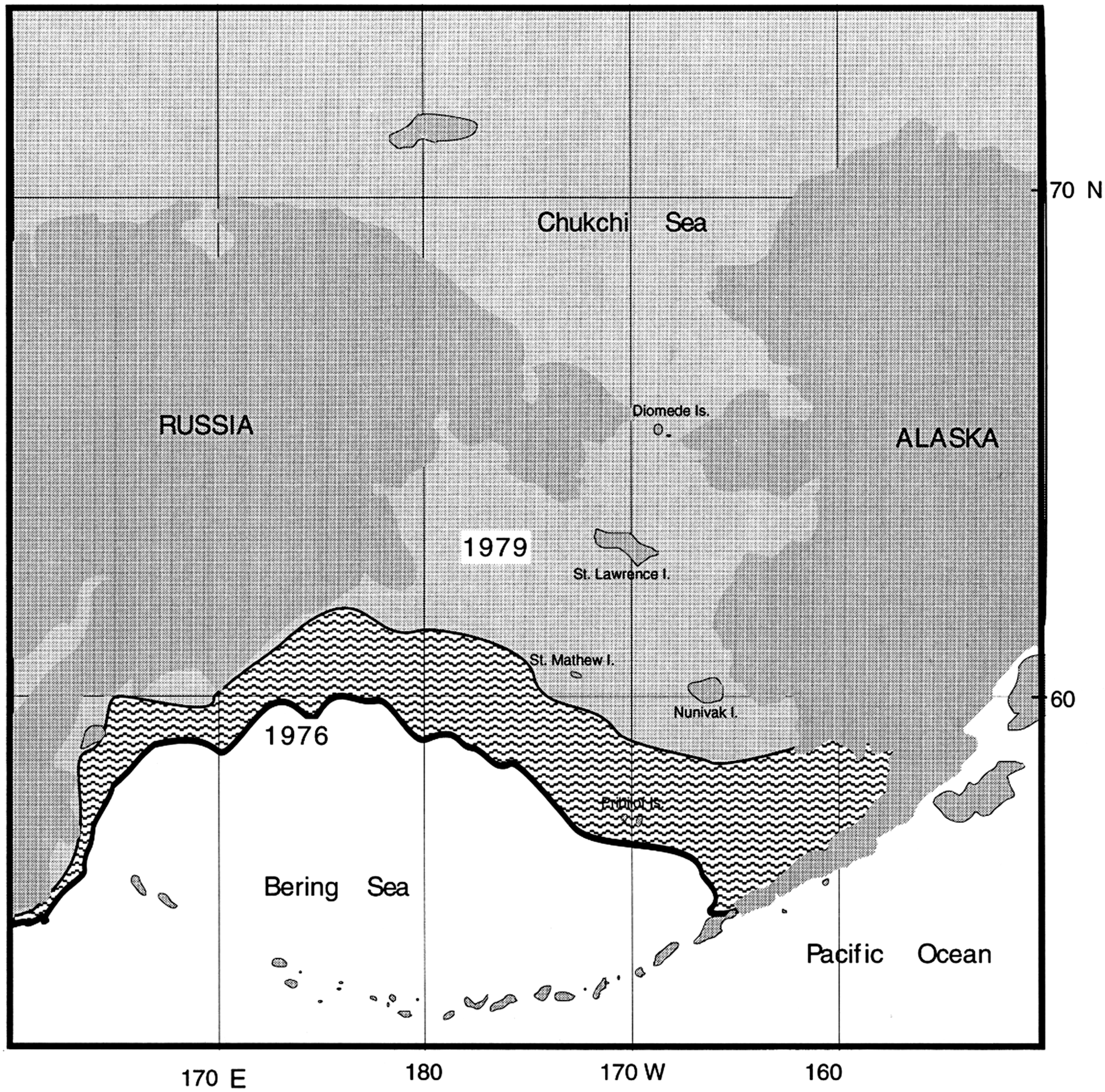

Figure 4. Sea ice extent over the Bering Sea in a heavy ice year (1976) and light ice year (1979). (Reproduced with permission from Wyllie-Echeverria (1995).

BIOLOGICAL SETTING

Gulf of Alaska Biological Setting

Phytoplankton biomass and production are strongly seasonal.

Zooplankton abundance is also seasonal. There are five dominant subarctic copepods found in the Gulf of Alaska: three species of the genus *Neocalanus* (*plumchrus, cristatus, flemingeri*), *Eucalanus bungii*, and *Metridia pacifica*. All of the dominant subarctic copepod species are found together or separately in coastal embayments surrounding the Gulf of Alaska. For example, *N. plumchrus* is abundant in the Strait of Georgia, while *N. cristatus* and *N. flemingeri* are apparently absent. Both *N. plumchrus* and *N. flemingeri* are abundant in Prince William Sound, where populations apparently build to extremely high levels through an estuarine–type circulation. Other fjords have primarily *E. bungii*.

The coastal regions of the Gulf of Alaska encompasses a major zoogeographic boundary for fish and crab species. Coastal regions off Southeast Alaska and British Columbia mark the northern boundary of transitional species common to the Oregonian zoogeographic province and the southern boundary of species common to the Aleutian Province (Allen and Smith 1988). The presence of this zoogeographic boundary makes the Gulf of Alaska a desirable location for research on responses of marine organisms to climate variability because the responses of marine stocks are more easily detected at the edges of their distribution.

The dominant species of pelagic fish are pollock, sockeye salmon and herring in order of abundance. Large spawning concentrations of pollock are found in the region near the Shumagin Islands, Shelikof Strait and Prince William Sound. Herring utilize nearshore regions around Kodiak Island, Prince William Sound and southeast Alaska for spawning. Large salmon runs are found in the Gulf of Alaska; one of the most famous runs is the Copper River sockeye run that returns through Prince William sound. Interactions between these three pelagic species is the primary focus of the SEAS research program in Prince William Sound. The SEAS study focuses on the possibility that when copepod abundance is high, predation of salmon and herring by pollock will be reduced.

The Gulf of Alaska also supports a large concentration of benthic fish and crab species. These species reside on the shelf and slope. The abundance of the benthic fish and crab population has been out of phase in recent years, the flatfish population has increased in abundance while the crab population has declined (Albers and Anderson 1985, Blau 1986, Wilderbuer 1994) (Fig. 5). Of notable importance is the increase in the arrowtooth flounder population, which now represents the largest biomass of fish in the Gulf of Alaska. Adult arrowtooth flounder are a major source of predation mortality in the region, consuming small fish as well as euphausiids (Livingston, in review).

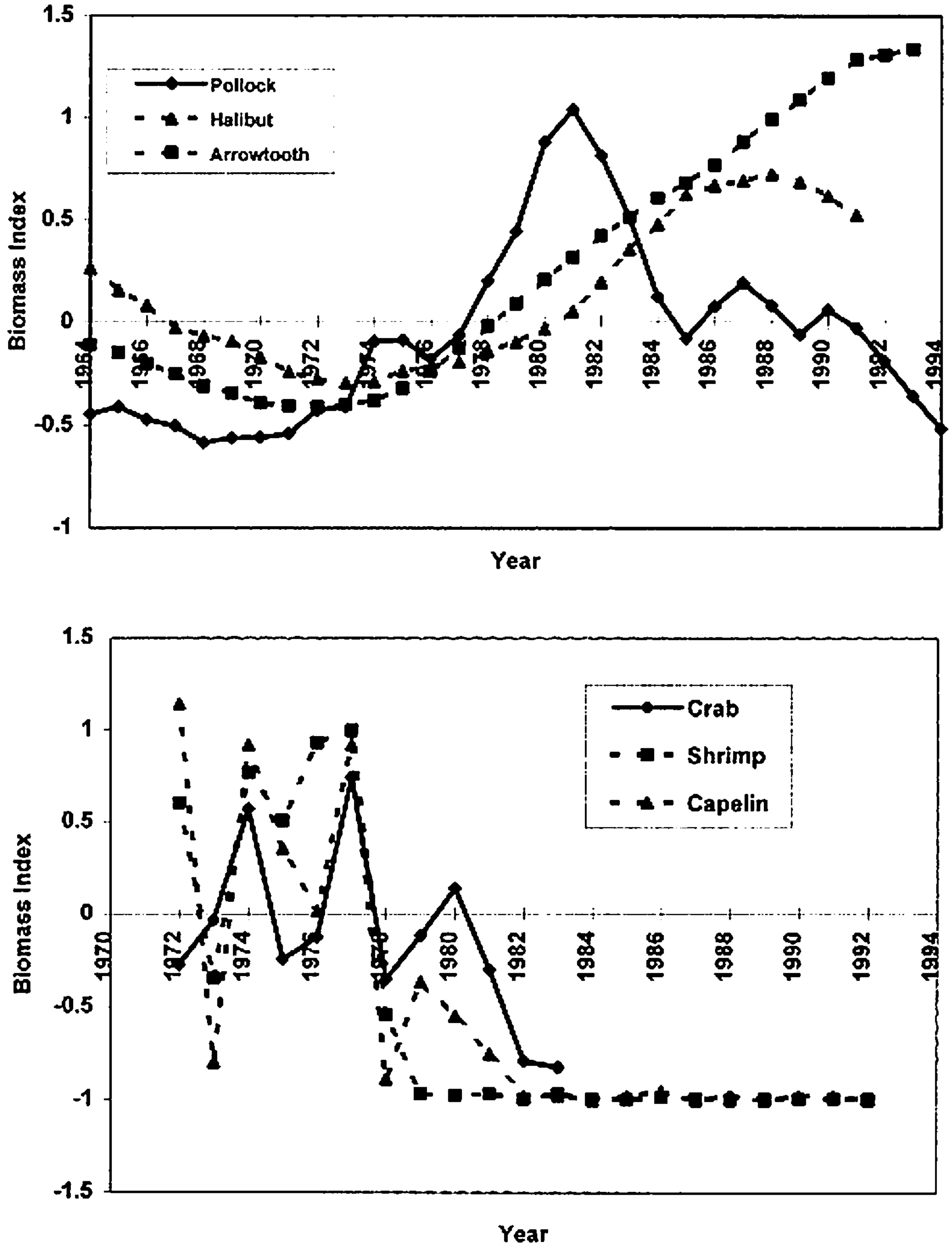

Figure 5. Indices of fish and shellfish biomass from the Gulf of Alaska. Fish biomass indices based on a base period of 20 years (1967-1986). Shellfish and capelin abundance indices based on a 10 year base period (1972-1983). (Hollowed, unpublished)

The mix of higher trophic level species appears to have changed during the late 1970s, coincident with a major change in ocean conditions.. Abundance of several pinnipeds declined in the region in the 1980s (Merrick et. al. 1987, Hatch and Sanger 1992). One of these, the Steller sea lion, is currently listed as a threatened species under the Endangered Species Act.

Subarctic Pacific

The climate of the Subarctic North Pacific Ocean changed during the late 1970s. The Aleutian Low intensified (Trenberth and Hurrell 1994). Sea surface temperatures rose rapidly by several degrees (Rogers and Ruggerone 1993; Royer 1989; Graham 1995). Strong physical and biological interactions occur on both seasonal and interannual time scales. Variations in the strength of the Aleutian Low result in large seasonal changes in atmospheric forcing (Wilson and Overland 1987).

There are several notable characteristics of living resources in the Subarctic Pacific. An unusual feature of the subarctic system is the absence of a spring phytoplankton bloom. Explanations for the absence of the bloom include lack of micronutrients such as iron or grazing by microzooplankton (Miller et al. 1991). The dominant copepods of the subarctic Pacific include three species of the genus *Neocalanus* (*plumchrus, cristatus, flemingeri*), *Eucalanus bungii*, and *Metridia pacifica*. Zooplankton biomass and the catches of epipelagic nekton increased after the mid 1970s (Brodeur and Ware 1992; 1995).

Salmon catches from the North Pacific increased sharply in the late 1970s, especially in Alaska, and exceeded historical levels (Pearcy 1992; Beamish and Bouillon 1993; Francis and Hare 1994). During this recent period of high production, evidence accumulated that several species of salmon, of both North American and Asian stocks, were returning as mature or maturing fish at increasingly smaller sizes (Kaeriyama 1989; Ishida et al. 1993; PICES 1993) (Fig. 6). This suggests density-dependent growth and competition for food in the ocean. Apparently, the carrying capacity of the Subarctic Pacific for salmonids, a major group of epipelagic fishes, was limited, even during this period of exceptionally favorable ocean conditions of the 1980s and 1990s. If the next climate shift is to cooler and less productive conditions, this problem will be exacerbated and have major economic consequences for nations along the Pacific Rim that produce wild and hatchery salmon (PICES 1993).

Besides changes in the productivity per unit area, global warming may also reduce the geographic area that is optimal for salmon growth and survival. Recent observations by Welch et al. (1995; in prep.) suggest that salmon may undertake a reverse, northward migration during the winter. If this is true, and if global warming continues, the area of suitable habitat for salmon could be severely restricted during that season.

Bering Sea

The Bering Sea is the most productive of the three study regions, supporting large stocks of marine fish, crab, seabirds and marine mammals. The eastern Bering Sea shelf can be divided into seven habitats or bio–physical domains (Fig. 7). These domains are separated by an outer, middle and inner frontal system. The physical and biological characteristics of the seven regions differ.

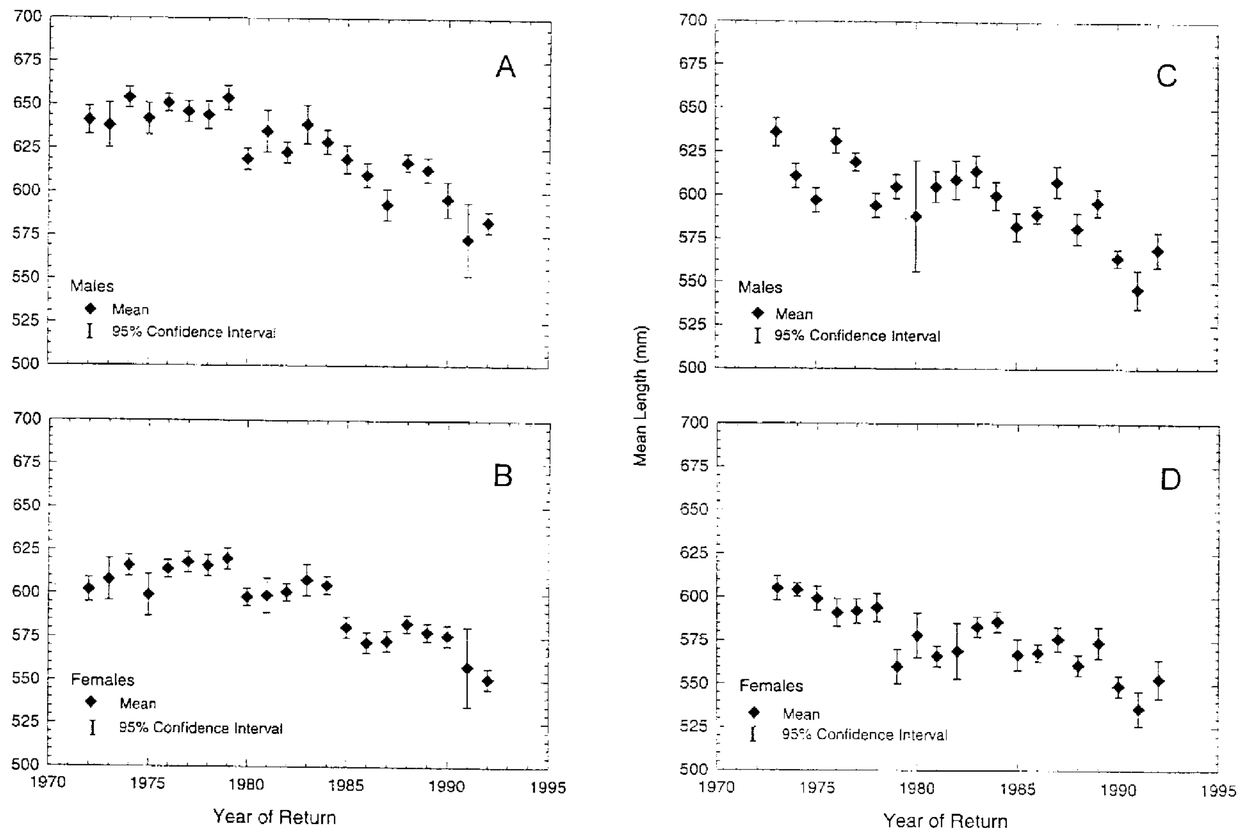

Figure 6. Mean length and 95% confidence interval of age-4 male and female chum salmon spawners at (A and B) Fish Creek, Alaska, 1972-1992 and (C and D) Quilcene National Fish Hatchery, Washington, 1973-1992. Reprinted from Helle and Hoffman (1995).

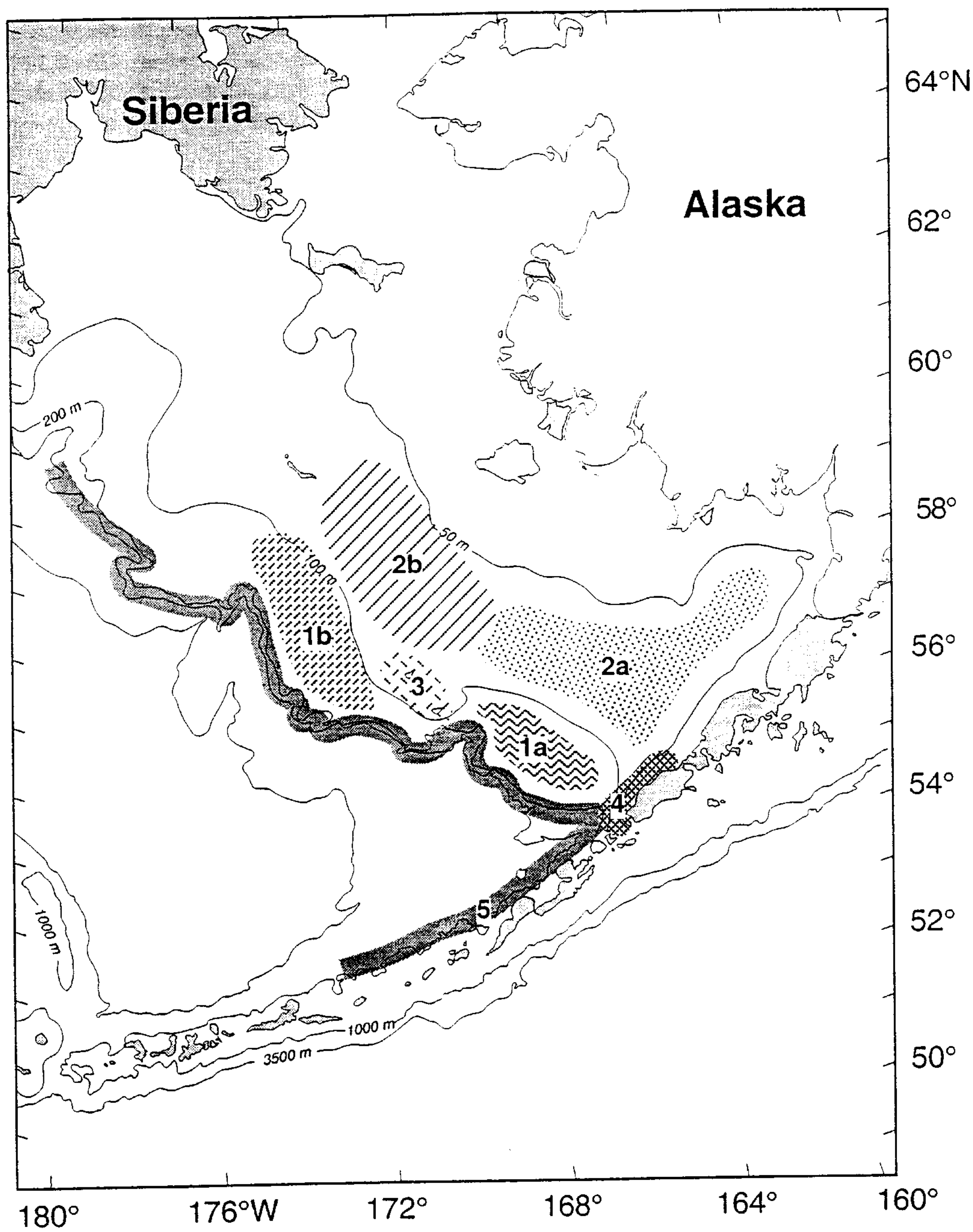

Figure 7. Habitats of the eastern Bering Sea: 1a and 1b) SE and NW outer shelf, 2a and 2b) SE and NW middle shelf, 3) Pribilof Islands, 4) Unimak Island, 5) shelf break. From the Southeast Bering Sea Carrying Capacity Concept Paper part of the National Oceanic and Atmospheric Administrations, Coastal Ocean Program.

Primary productivity on the southeast Bering Sea shelf is spatially variable and highly episodic. Spring blooms are associated with the ice edge and thermal stratification is an important factor in determining whether the production remains in the pelagic or benthic system. Studies indicate that the production on the southeastern Bering Sea shelf is limited by the transport of nutrients onto the shelf from the basin.

Pollock is the dominant species of pelagic fish in the Bering Sea. Large spawning concentrations of pollock are found in the Bogoslof region and the southeast Bering Sea Shelf. Pollock play an integral part in the Bering Sea ecosystem, representing the most abundant forage fish species for marine mammals and sea birds and a major consumer of copepods and euphausiids. Adult pollock may regulate their population size through cannibalism.

The Bering Sea also supports a large concentration of benthic fish and crab species. These species reside on the Bering Sea shelf and mainly consume benthic infauna. The abundance of the benthic fish and crab population has been out of phase in recent years, the flatfish population has increased in abundance while the King Crab population has declined.

Seabirds and marine mammals are abundant in the Bering Sea. Several species of whales migrate to the region to feed. The Pribilof Islands are an important region of pinniped (northern fur seal) and seabird (kittiwakes and murres) breeding in the summer.

BREAKOUT SESSION 1—Climate Change Scenarios

What are likely scenarios for climate change in the North Pacific and how would they influence the ecosystem?

Discussion Leaders: Nick Bond and Robert DeLong
Participants: Richard Beamish, Steve Hare, Steve Ignell, Evelyn Lessard, Allen Macklin, Brenda Norcross, Jim Overland, William Peterson, Alan Springer, Ted Strub, Ron Thom, Cynthia Tynan.

This breakout session was devoted to discussions of potential impacts of regime shifts possibly caused by increased CO_2 from anthropogenic activities and subsequent warming (the greenhouse effect). Case studies were presented for possible impacts of global warming in the Gulf of Alaska and Subarctic Pacific (Table 1), and Bering Sea (Table 2). These case studies are discussed in detail in Appendix 1. These case studies were tentative and served to initiate discussions for this breakout group.

Summary of Discussions:

Although the group discussed some likely scenarios for climate change in the North Pacific, the group decided to defer to climatologists who will generate detailed predictions of climate changes that are likely to occur in the areas of interest: the Subarctic North Pacific, Gulf of Alaska, and the Bering Sea. The ecosystem of the North Pacific Ocean will be sensitive to the geographical distribution of the changes in the atmosphere–ocean climate system. These distributions are not yet reliably predicted by climate models. But U.S. GLOBEC need not wait until these models are improved and verified. Studies of how physical forcing couples to the ecosystem now will help to anticipate changes in the latter, no matter how the climate evolves. Short–term (seasonal) to long–term (decadal) climate variations appear to significantly impact the biological environment (see collection of papers in Beamish (1995)). The interdependence of these climate fluctuations and the nature of the biological responses can be used as a proxy for at least some aspects of future long–term changes. A combination of retrospective, monitoring, and process studies should be used to document and better understand current linkages between changes in the physical and biological environments. This working group has identified four key aspects of the physical environment for which long–term changes would have an especially profound effect on the biology.

1) Mixed Layer Depth

Time variation in late spring/summer mixed layer depth is the physical oceanographic measurement which may correlate most highly with primary and secondary productivity in the coastal Gulf of Alaska and Bering Sea shelf. The spring phytoplankton bloom depends on stratification of the water column to retain cells above the depth at which light levels allow positive net production. After the bloom has begun and when nutrient depletion is imminent, mixing can prolong production by large phytoplankton cells by providing new nitrogen (sensu Dugdale and Goering, 1967) from below the nitricline. Variability in summertime mixed layer depth would generally be expected to indicate the active mixing and introduction of new nitrogen.

Table 1. Hypothesized physical changes in the Subarctic Pacific under a global warming scenario.

Physical Process	**Hypothesized Change**
Wind Stress Curl	Decreases, northward shift
Poleward Transport	Position of subarctic bifurcation moves north; changes in transport unknown
Coastal wind stress	Decreases, esp. winter
Coastal downwelling	Decreases, esp. winter
Coastal precipitation	Increases
Freshwater input	Increases; maximum shifts toward winter
Coastal current transport (ACC)	Decreases
Stratification	Increases in central gulf and in coastal region
Upwelling, central Gulf of AK	Decreases
SST	Increases
Eddies and meanders	Unknown
Mixed layer depth	Decreases
Cross shelf transport	Decreases
Winter storms intensity	Decreases
Winter storm frequency	Unknown
Timing of spring bloom	Unknown; may be later due to lower temperatures, or earlier due to decreased cloudiness affecting solar timing.

Table 2. Hypothesized physical changes in the Bering Sea under a global warming scenario.

	Physical Process	Hypothesized Change
I. Atmosphere		
	Surface air temperatures	Increase
	Storm intensities	Decrease
	Storm frequencies	Increase
	Sea level pressure	Decrease in N. Bering
	Southerly wind	Increase
	Humidity	Increase
	Precipitation	Increase
	Fresh water runoff	Increase
II. Circulation and Transports		
	Alaskan Stream	Probable decrease
	Near Strait Inflow	Decrease
	Bering Slope Current	Decrease
	Kamchatka Current	Decrease
	Bering Strait Outflow	Unknown, competing effects
	Unimak Pass inflow	Unknown
	Shelf coastal current	Unknown
III. Hydrography		
	Sea level	Increase
	Sea surface temperature	Increase
	Shelf bottom temperature	Increase
	Basin stratification	Increase
	Shelf stratification	Unknown, competing effects
	Mixing energy	Decrease
	Eddy activity	Unknown
	Shelf break nutrient supply	Decrease
IV. Sea Ice		
	Extent	Decrease
	Thickness	Decrease
	Brine rejection	Decrease

In the open Subarctic Pacific, predicting the influence of climate change on the mixed layer depth and the response of phytoplankton to this change is more complex. There, iron, a micro-nutrient, limits phytoplankton growth; its suspected source is dust carried with the winds from Mongolia/Siberia (Miller et al. 1993). Variation in mixed layer depth may have little affect on annual production in this region. On the other hand, higher mean irradiance in the mixed layer may increase primary production in the Subarctic Pacific. This increase in primary production may increase the recycling time of iron and the available iron may sustain populations longer.

The Bering Sea Shelf has three distinct hydrographic and biological regimes (Coachman, 1986; Cooney and Coyle, 1982). Hydrographic structure and mixing is determined by the balance and depth of influence of wind versus tidal mixing. Climate change is not expected to strongly affect the net mixing over the shelf, although there are likely to be changes in the annual cycle of stratification over the shelf and near the shelf break, due to changes in sea ice melt, insolation, wind forcing, and the mean currents. It is possible that the waters will be well mixed during a larger portion of the year which may increase productivity if there is sufficient light available for positive net production. On the other hand, if nutrients are limiting, increased mixing would only enhance production where a nutrient reservoir beneath the pycnocline exists. Yet another scenario would predict that increased cloudiness would decreased the amount of light and production might decrease.

2) Changes in Marine Habitat (Volume and Location)

Oceanographic warming is expected to have density dependent effects on the growth rate, size, and survival of salmon. Increases in salmon habitat in the open subarctic due to warming could increase growth or survival resulting in larger or more or fish in the future than there are today (similar responses might occur in other species). The species mix within the salmon guild may be somewhat different than it is today because warmer marine temperatures may favor one species over another.

The response of marine communities to climate change may differ in the Bering Sea and Gulf of Alaska because of the location of the species within its zoogeographic range (Bailey and Incze 1985). In the Gulf of Alaska, where some species are at the southern edge of their range, warm ocean conditions may cause poor survival. In contrast, in the Bering Sea, some species are at the northern edge of their range, and warmer ocean conditions may favor survival and expansion into new habitats.

3) Sea Ice

Under most global warming scenarios, sea ice distribution is expected to decrease both in time and space. An ice free Bering Sea shelf might increase spawning habitat for demersal species such as pollock. The ice free environment would delay the spring bloom because of a delay in the establishment of water column stability and lack of seed populations of ice algae. The spring bloom over the shelf has been shown to be delayed by about two weeks south of the ice covered regions. The retreat of the ice to a higher latitude of the Bering Sea or Bering Straits would dramatically alter the distribution of five species of ice dwelling pinnipeds which use the ice edge for rookery habitat and change levels of predation on fish and invertebrates of the Bering Sea shelf. Other marine mammal and seabird species would likely occupy the open waters of the Bering Sea during times of the year when they are now excluded by ice coverage.

4) River Flows (Precipitation)

With global warming, there may be significant changes in precipitation patterns and in river flows feeding into the Bering Sea, Gulf of Alaska, Southeast Alaska and Canada. High latitude Alaskan rivers may remain ice free for longer periods of the year increasing their production capacity for salmonids whereas rivers in southern British Columbia may have lower snowpack thereby decreasing their capacity for freshwater production of salmon. Both spawning success and juvenile survival can be expected to change in response to shifts in river flow characteristics which will be mediated by climatic warming.

Coastal currents can be expected to be enhanced during much of the year due to increased rainfall, but perhaps be less variable in that less of the volume of water will originate from snow and glacial melt. Stronger currents may be expected to cause increases in advection of plankton and some nekton as well as transport of nutrients.

BREAKOUT SESSION 2—Regime Shifts and Decadal Shifts

Regime and decadal scale shifts: can they be detected, what is their impact, are they predictable?

Discussion Leaders: Tom Royer and Anne Hollowed
Participants: Vera Alexander, Tim Baumgartner, Dan Cayan, Bruce Frost, Nick Graham, Scott Hatch, Jim Ingraham, Nate Mantua, Pete Rand, Gary Sharp, Beth Sinclair.

Long term variations in ocean conditions appear to occur at different time scales and the biological responses appear to differ in magnitude. The temporal periods most commonly mentioned are: a) decadal and bi-decadal scale shifts, 6-12 year warm cool eras (Trenberth and Hurrell, 1994; Hollowed and Wooster, 1992), b) cyclic phenomenon such as the 18.6 year pattern in sea surface temperature (Royer, 1993), and c) regime shifts that are 30–60 year cycles and appear to generate measurable ecosystem responses (Francis and Hare, 1994; Baumgartner et. al., 1992, Kawasaki. 1991). Many studies indicate that a marked change in ocean conditions occurred in the late 1970s which some believe was a regime shift, that is, a rapid change from one stable condition to another. Some effort should be devoted to distinguishing the similarities or differences between these three longer term processes.

1) Can they be detected?

Indications of decadal scale and regime shifts might be detected at high latitudes in the northern North Pacific in both the atmosphere and ocean. Trenberth and Hurrell (1994) found the North Pacific winter sea level pressure between 30° and 65°N and 160°E and 140°W shows a mean pressure of about 1010 mb from 1946 to 1977, changing to about 1007 mb from 1977 to 1988 when it changed back to about 1010 mb (Fig. 8a). The timing of blocking marine ridges has changed from being primarily in winter in the early 1970s to primarily in fall in the late 1970s (Salmon, 1992). In contrast to this potential regime shift, the low frequency components of the sea level pressure since 1925 suggest a more cyclic pattern of variability (Trenberth and Hurrell 1994) (Fig. 8b). Cayan (In Prep.) shows pseudo stress ($m\ s^{-2}$) anomalies obtained from the differences in states existing before and after the shift of 1976–77 which suggests an intensification of cyclonic winds in the Gulf of Alaska between these two periods (that is a warming) (Fig. 9). Ingraham (Pers. Comm., Alaska Fisheries Science Center, Seattle, WA) used the Ocean Surface Current Simulations (OSCURS) model to generate wind driven surface drift trajectories initiated during winter months (Dec.–Feb.) from Station P for the period 1946 to the present. The endpoints of these 3-month drift trajectories shifted in a bimodal pattern to the north and south around the mean. Thus, the winter flow during each year is persistent enough to, result in a large displacement of surface mixed layer water. The displacement also varies in a decadal pattern. Using the rule that the present mode is maintained until 3 years in a row of the opposite mode occur (Fig. 10) four mode shifts were suggested; a south mode from 1946 to 1956, a north mode from 1957 to 1963, a south mode from 1964-1974, and a north mode 1975 to 1994.

Temperature anomalies in the Gulf of Alaska and Bering Sea illustrate a relative warm period in the late 1950s followed by cooling especially in the early 1970s followed by a rapid temperature increase in the latter part of that decade. Since 1983, the Gulf of Alaska and Bering Sea have

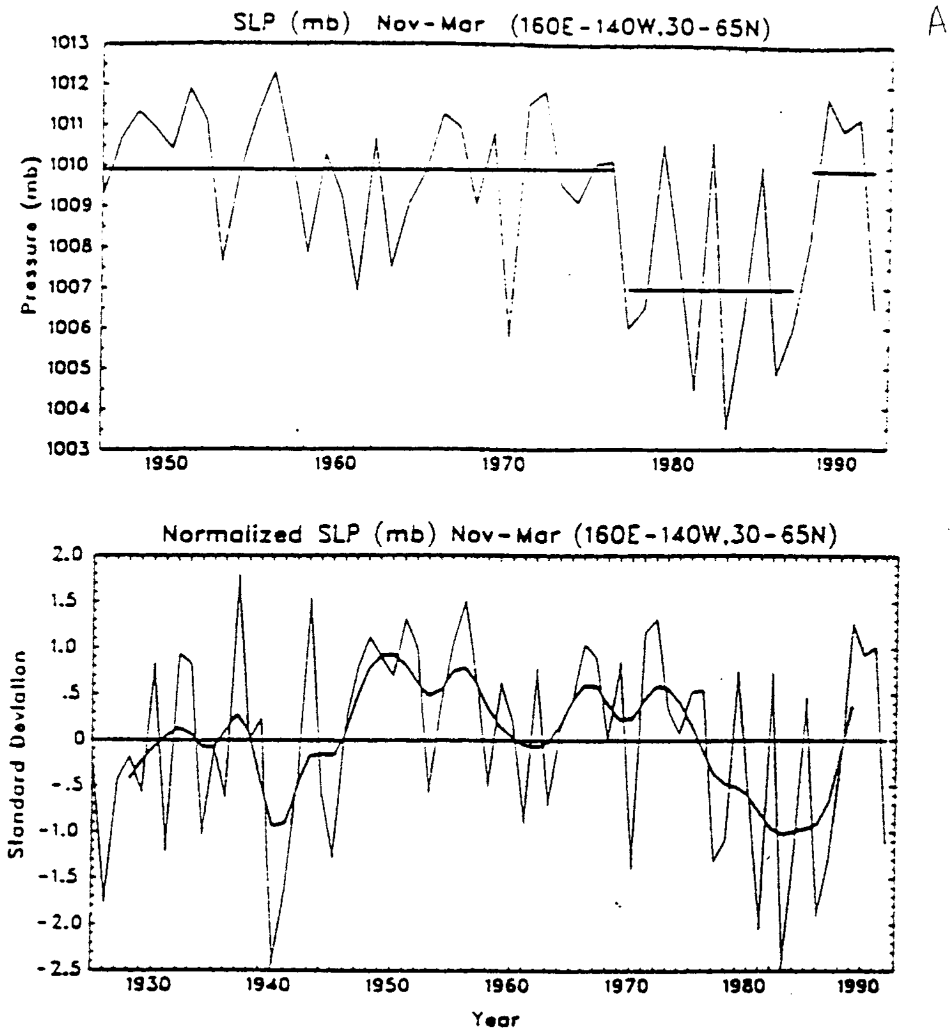

Figure 8. Panel A (top) is the time series of mean North Pacific sea level pressures averaged over 30° to 65°N, 160°E to 140°W for the months November through March. Means for 1946-1976 plus 1989-1992 and 1977-1988 are indicated (where 1988 refers to the 1987-88 winter). Panel B (bottom) is the time series of mean North Pacific sea level pressures for November through March, as in panel A, but beginning in 1925 and smoothed with a low pass filter. From Trenberth and Hurrell (1994). (Reproduced with permission.)

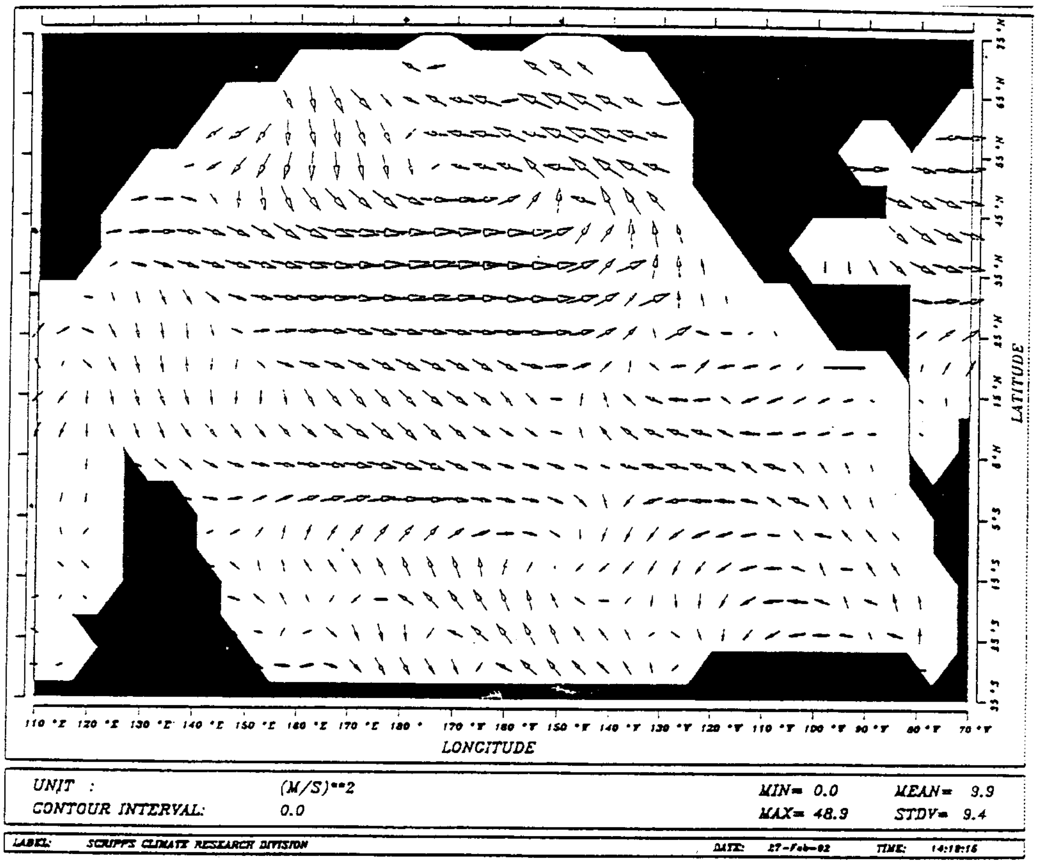

Figure 9. COADS/FSU winter pseudo stress component differences between 1977-1982 and 1971-1976. From UNESCO (1992).

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Figure 10. Summary of directions (north or south) of flow anomalies indicated by OSCURS model generated surface drift trajectories started at Station P for winter months December-February. The year indicates the starting year (December). From Ingraham (pers. comm., Alaska Fisheries Science Center, Seattle, WA).

undergone different temperature changes. The sea surface temperature in the Gulf of Alaska were generally above normal and those in the Bering Sea were below normal. The temperature differences between the two bodies of water have jumped from about 1.1°C to about 1.9°C (Figure 11). Subsurface temperature anomalies for the coastal Gulf of Alaska (GAK1, 60°N, 149°W) also show a change from the early 1970s into the 1980s similar to that observed in the sea surface (Fig. 12). In addition, high latitude temperature responses to ENSO events can be seen especially at depth in 1977, 1982, 1983, 1987 and in the 1990s.

2) Potential Causes of Climate Decadal Scale Variability

The high latitude ocean temperature variability results from a number of possibly independent physical processes such as the seasonal, 3–4 year and 6–7 year wind stress, El Niño–Southern Oscillation and lunar nodal tidal (18.6 year) signals. Trenberth and Hurrell (1994) argue that the shift in the atmospheric circulation over the North Pacific in the middle 1970s can be attributed to the onset of a period of enhanced El Niño activity. Graham (1994) argues that this shift is more associated with an increase in the background mean SST in the tropical Pacific. A host of studies (e.g., Horel and Wallace 1981) have documented the atmospheric link between the tropical and North Pacific. On the other hand, recent GCM results have shown that the North Pacific ocean–atmosphere climate system can oscillate on time scales of approximately 20 years, independent of tropical forcing (Latif and Barnett 1994). The evidence of these causal mechanisms is principally found in modeling and comparative studies. For example, a proxy of ocean temperature over the last 166 years has been constructed using air temperatures at Sitka, Alaska. This proxy time series contains lower frequency variations that are possibly a response to lunar nodal tide forcing (18.6 year) (Royer, 1993) (Fig. 13). Research that will improve our understanding of potential forcing mechanisms influencing longer term variations are an important topic for U.S. GLOBEC investigations.

3) Biological Impacts of Climate Variability

Decadal scale changes in the distribution and abundance of marine populations have occurred coincident with shifts in the physical environment. Francis et al. (in review) review the impacts of the most recent regime shift through lower, secondary and top trophic levels of the North Pacific marine ecosystem. Some of the following summaries are taken from this review.

Population trends of zooplankton in the Subarctic Pacific and California Current show opposite trends in recent years. Evidence of lower trophic level responses to decadal scale climate change is provided in the increase of subarctic zooplankton abundance from the 1950s to the 1980s reported by Brodeur and Ware (1992) (Fig. 14). Roemmich and McGowan (1995) used the CalCOFI time series to document declines in zooplankton biomass between the 1950s and 1980s off southern California.

Abundances of higher trophic level consumers are available for commercially important fish and shellfish stocks (shrimp and crab). Most of the biological time series for these species are comparatively short (they span only two physical states: cool and warm). Notable exceptions are the Pacific halibut and Pacific herring recruitment time series, the Pacific salmon catch, and northern fur seal population data collected on rookeries. These time series extend back to the

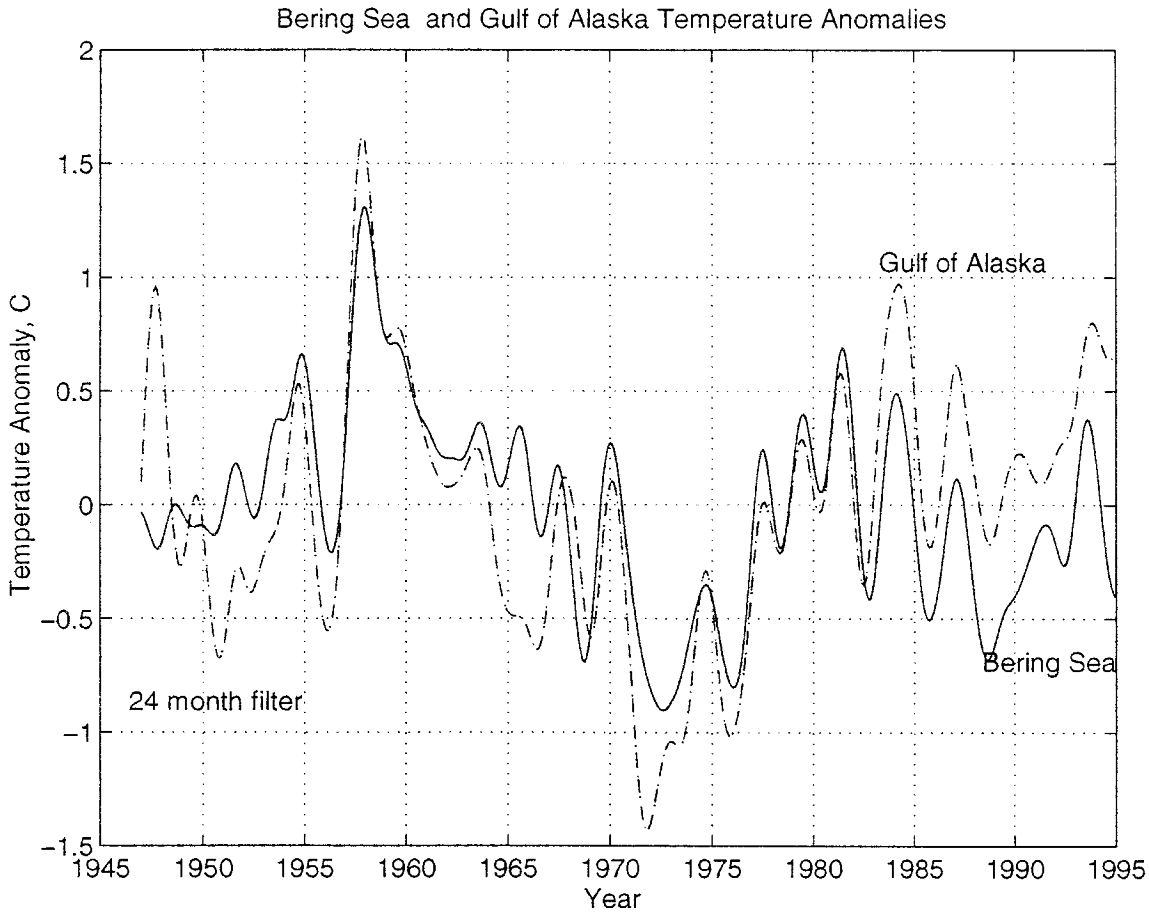

Figure 11. Sea surface temperature anomalies for the Bering Sea (55°N, 170°W) and the Gulf of Alaska (55VN, 160°W) with 24 month filter. Data are from Dan Cayan, Scripps Institution of Oceanography, La Jolla, CA.

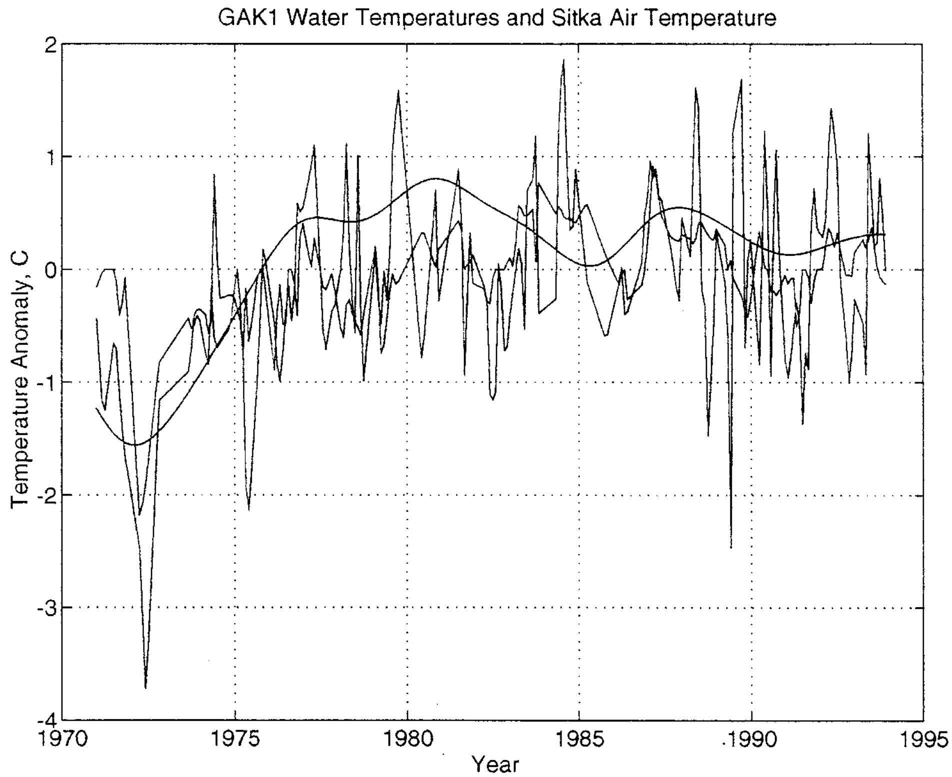

Figure 12. Sitka air temperature anomalies (smooth curve), GAK 1 sea surface temperature anomalies (largest variations) and GAK 1 temperature anomalies at 250 m. Modified from Royer (1993).

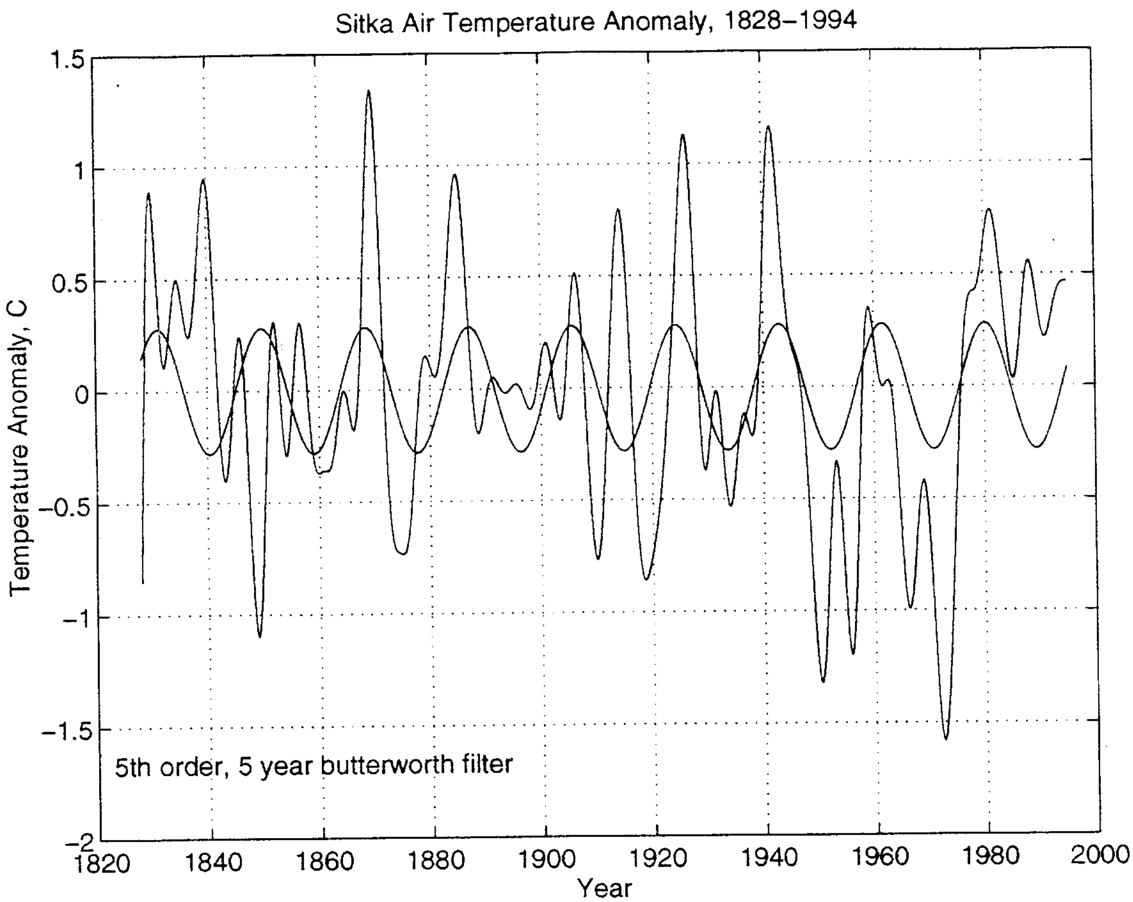

Figure 13. Air temperature anomalies from Sitka, Alaska filtered with a 5 year low pass filter. These can be used as a proxy for ocean temperatures. A least squares fit of the lunar nodal tide (18.6 yr.) is also shown (After Royer 1993). Reproduced with permission.

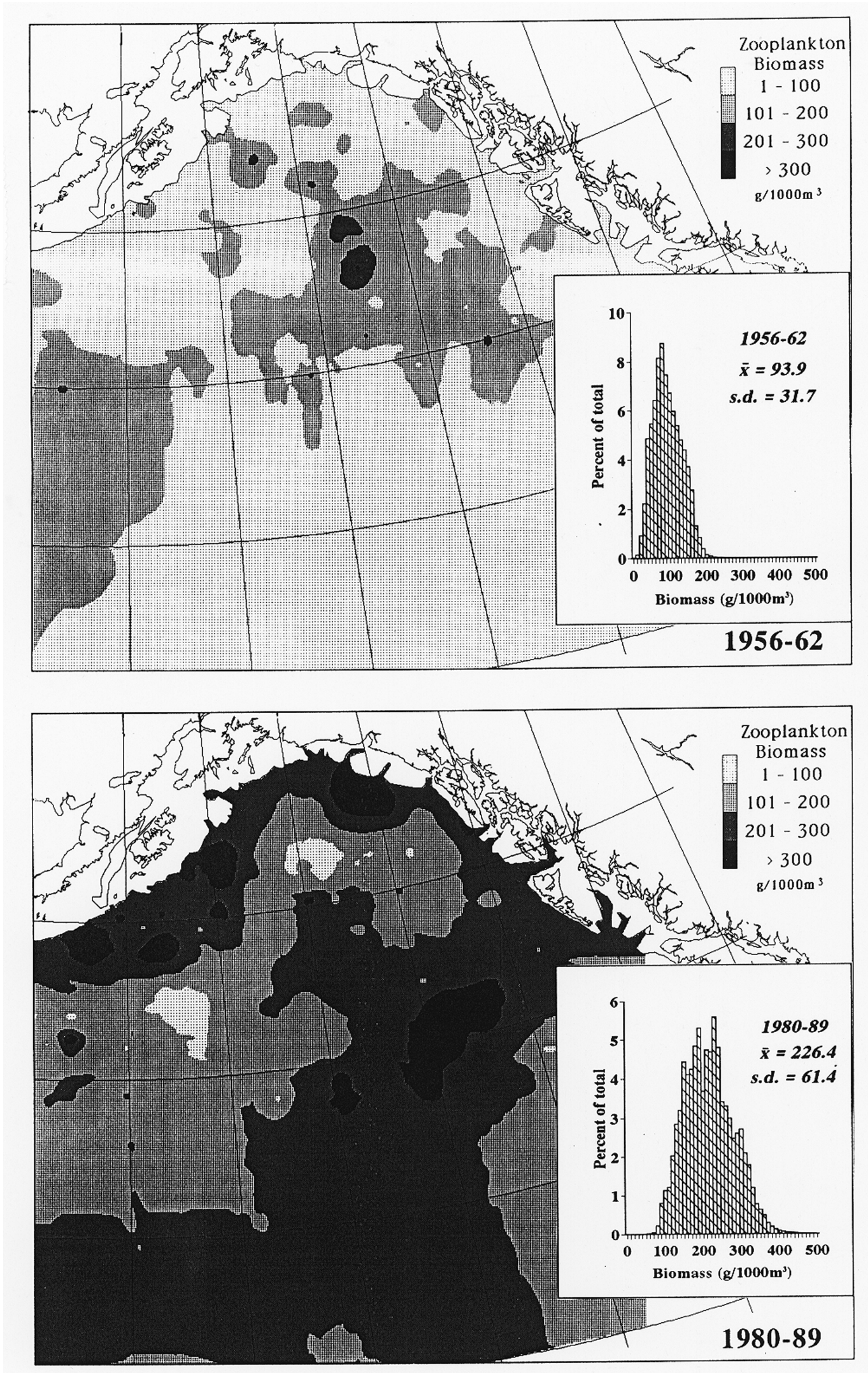

Figure 14. Summer biomass distributions of zooplankton collected in 1956-1962 (top) and 1980-1989 (bottom) in the North Pacific. The distributions are composites of sampling from June 15 to July 30 and over the years indicated. (from Brodeur et al., in press, reproduced with permission of the author).

early 1900s. Parker et. al. (1995) show marked similarities between time series of the lunar nodal tidal cycle, and recruitment patterns of Pacific halibut. Hollowed and Wooster (1995) examined time series of marine fish recruitment and observed that some marine fish stocks exhibited an apparent preference (measured by the probability of strong year classes and average production of recruits during the period) for a given climatic regime. Hare and Francis (1995) found a striking similarity between large scale atmospheric conditions and salmon production in Alaska. Quinn and Niebauer (1995) studied the Bering Sea pollock population and found that high recruitment coincided with years of warm ocean conditions (above normal air and bottom temperatures and reduced ice cover). This fit was improved by accounting for density dependent processes. Livingston and Methot (in review) estimated the abundance of age–1 pollock in the Bering Sea before predation (primarily cannibalism) occurred. Using this abundance index, a marked shift in the mean recruitment was observed before and after the regime shift (Fig. 15).

On a larger scale, evidence of biological responses to decadal scale changes in climate are also found in the coincidence of global fishery expansions or collapses of similar species complexes. Examples include the recent increase in the South American and Japanese sardine stocks and their subsequent fisheries expansions (Kawasaki 1991).

Climate effects on seabirds are primarily indirect, affecting the availability of preferred prey and composition of marine fish stocks. Attempts to correlate seabird responses (breeding productivity in particular) with simple physical parameters such as sea surface temperature have given mixed results. Hunt et. al. (in press) provide an example of the potential impact of climate change on prey availability of seabirds on the Pribilof Islands in the Bering Sea. These authors found the proportion of age–1 walleye pollock in seabird diets decreased between the 1970s and 1980s, while during the same period, the proportion of age–1 pollock in NMFS bottom trawl hauls decreased in the vicinity of the Pribilof Islands. Since the decrease in age–1 pollock in the diet was observed in both surface and subsurface feeding seabirds, the authors conclude that the change resulted from a horizontal change in the distribution of age–1 pollock in the vicinity of the Pribilof Islands.

Hatch and Sanger (1992) and Springer et. al. (1986) examined the potential impact of changes in the abundance of seabird prey. Springer et. al. (1986) found the reproductive success of kittiwakes in the Bering Sea was related to indices of juvenile pollock abundance. However, more recent analyses of Decker et al. (1995) and Hunt et al. (1995) suggest that the availability of forage fish is more important than the abundance of pollock in determining the reproductive success of kittiwakes on the Pribilof Islands. Hatch and Sanger (1992) found the importance of juvenile pollock in the diet of tufted puffins in the Gulf of Alaska was positively related to estimates of year–class strength of juvenile pollock.

Piatt and Anderson (1995) provide evidence of possible changes in prey abundance due to decadal scale climate shifts. These authors examine relationships between significant declines in marine birds in the northern Gulf of Alaska during the past 20 years and found significant declines in common murre populations occurred between the mid to late 1970s and the early 1990s. Piatt and Anderson (1995) found marked changes in diet composition of five seabird species collected in the Gulf of Alaska between 1975–78 and 1988–91. There was a shift in diet

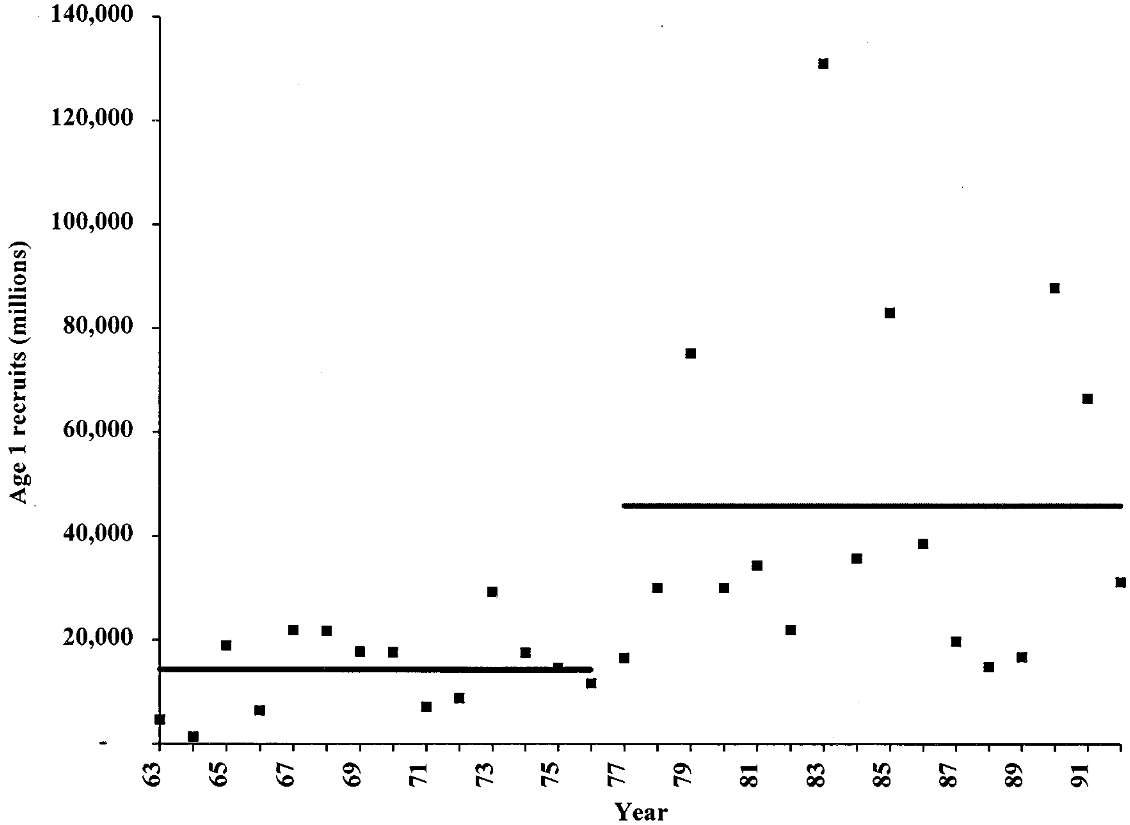

Figure 15. Estimates of age 1 pollock abundance from a stock synthesis model that includes predation effects. Mean recruitment for the period before and after 1977 is identified. Based on data presented in Livingston and Methot (in review).

from one dominated by capelin in the late 1970s to one where capelin was virtually absent in the later period.

Evidence of direct linkages between changes in the physical environment and survival of marine organisms exist for several species in the North Pacific and Bering Sea. For example, York (1991) examined the relationship between sea surface temperature and survival of male northern fur seals from the Pribilof Islands. After accounting for age–specific harvest of fur seals, York's analysis showed strong correlations between SST and survival. She suggested that the relationship could be related to the influence of SST on the availability of food for young fur seals.

Pinnipeds are considered specialized generalists feeding on a variety of prey types with notable preferences for particular types of prey. If the number of alternative prey types is low, then prey availability may have a significant impact on survival. The species composition of the diet of marine mammals before and after the late–1970s regime shift was different. Merrick and Calkins (in press) examined the prey items of Steller sea lions during 1975–1978 and 1985–1986. This study showed walleye pollock were the most common prey item in the diet in virtually all seasons and areas of the Gulf of Alaska before and after the regime shift. Their work showed an increase in the proportion of sampled animals that consumed pollock from the 1970's to the 1980's despite a decrease in the abundance of 2–3 year–old pollock. They show that while juvenile pollock declined in abundance, a simultaneous decline in the abundance of alternative prey may have occurred. They suggest that this simultaneous decline in abundance may have contributed to sea lion population declines in this region.

4) Paleoceanographic Record

Paleoceanographic data are an important element of research on longer term climate affects on marine ecosystems. High-resolution paleoceanographic data from sites with detailed chronologies of annual to near-annual precision provide a long-term historical context of the interdecadal variability in ecologically and economically important populations as well as the background ocean environment. The record of the Santa Barbara Basin, off southern California is the most complete so far, yielding a history of the sardine, anchovy and hake populations slightly longer than the past 1500 years. Currently under development are time series of oxygen isotope history from planktonic foraminifera (for ocean temperatures), analysis of the diatom and radiolarian assemblages, as well as radiocarbon measurements of a planktonic pteropod as a measure of the age of the near-surface waters (an indication of large-scale upwelling). The 1500-year record of the sardines and anchovies supports the existence of basin-scale interdecadal shifts in ocean climate. A major objective of the investigation of these records is to determine the characteristic time scales of variability to aid in understanding the nature of the decadal scale regimes including the biological response, and to likewise aid in predicting their duration.

Although sites such as the Santa Barbara Basin which can be used for high-resolution paleoceanographic reconstruction are rare (resulting from anaerobic bottom conditions found along continental margins), the interest generated by such programs as U.S. GLOBEC and PICES has stimulated the search for sites in the Subarctic Pacific so that the information from the Santa Barbara Basin can be linked to a more complete geographic network which we hope will include the region of the Alaska Peninsula (Skan Bay, Unalaska Is.) plus selected fjords of British

Columbia (e.g., west coast of Vancouver Is.) in which signals from the open ocean may be preserved. The Skan Bay site has been confirmed but not exploited, and a cruise is planned for December, 1995, to explore promising sites off Barkley and Nootka Sounds on Vancouver Island. The Vancouver Island sites are of particular interest because of their potential to register the northern expansion of the Pacific sardine during periods of warming along the west coast of North America. Such an expansion occurred during the 1930s when sardines were abundant from Baja California, Mexico, to Vancouver Island, and a significant fishery was established along the west coast of the island.

5) Need for Additional Research

The previous section presented compelling evidence of a coupling between large scale, multi–year climate variability and ecosystem responses. However, additional research is required to improve our understanding of the mechanisms underlying regime shifts in the physical environment, and the response of the ecosystem to regime shifts. Knowledge of the functional relationships between climate forcing and the physical and biological system is needed.

If the past reflects the future, it is possible to speculate potential impacts of future changes in climate on marine ecosystems. If the climatic regime returned to a state similar to that observed in the early 1970s, one might expect zooplankton production in the Subarctic Gyre might move offshore and overall production would decrease. A marked shift in the production of commercially exploited fish stocks in the North Pacific would be expected. Alaskan salmon and Bering Sea pollock production would be expected to decrease in the cooler regime.

6) Are they predictable and can they be simulated?

Indications of decadal scale shifts might be detected in time series of some or all of the following physical variables: sea level pressure, sea level pressure gradients, upper level pressures and gradients, cloudiness, turbidity, precipitation, sea surface temperature, temperature gradients, sea surface salinity, stratification, sea level, coastal and altimeter measurements of sea height, currents, transport and mixed layer depth.

Biological indicators of climate change include: abrupt changes in recruitment or in the frequency of extreme year classes, changes in the vertical or horizontal distribution of pelagic species, changes in trophic phasing (match–mismatch), changes in species dominance or species mix, changes in somatic growth, changes in bioenergetics, shifts in predator and/or prey.

North Pacific basin physical modeling results show promise in simulating and explaining monthly and decadal fluctuations of the thermal and dynamic properties over the mid–latitudes over relatively coarse scales. However, elements of the freshwater flux forcing (evaporation–precipitation, runoff) have not been incorporated and validated. These elements affect the mixed layer and are key in the structure of the upper layers in the subarctic region north of 40°N. Modeling efforts of the 1970–88 period by Miller (1994) successfully simulated the 1976–77 shift in the upper ocean temperature over the Pacific. Diagnosis of the model results show that this shift was a basin–wide phenomenon which occurred as a transition between two relatively stable but distinct regimes of ocean–atmosphere coupling. This change produced a reorganization of the structure and circulation of both the ocean and atmosphere. Models such as this may be useful in predicting future changes in the North Pacific system. Regional and mesoscale ocean models that are either driven directly by observed forcing or nested within larger scale ocean general circulation models (GCM) have been developed for the Gulf of Alaska through the FOCI program but they need to be developed in other regions of the North Pacific and expanded to include other species. Short term projections (1–2 years) of fish production based on observed ocean characteristics show promising results (Megrey et. al. in review).

BREAKOUT SESSION 3—Carrying Capacity

What is carrying capacity?

Discussion Leaders: Dan Costa and Jim Schumacher
Participants: Karl Banse, George Boehlert, Robert Haney, George Hunt, Patricia Livingston, William Pearcy, Daniel Ware.

Working Definition

Carrying capacity is a measure of the biomass of a given population that can be supported by the ecosystem. The carrying capacity changes over time with the abundance of predators and resources (food and habitat). Resources are a function of the productivity of the prey populations and competition. Changes in the physical and biotic environment affect the distributions and productivity of all populations involved.

The group agreed that carrying capacity exists, however they did not believe that it was worthwhile to attempt to measure it as an absolute value. Further, it was not instructive to attempt to provide a rigorous definition that would facilitate its direct measurement. Rather, they assumed that when a species approaches carrying capacity, density dependence will start to affect the important population parameters. Developing a set of parameters that can be used to assess the relative changes in the status of a population would be a useful exercise (Table 3). These parameters will vary with the scale of the system and the relative importance of abiotic (forcing & temperature) effects. To this end, it was informative to describe the various levels of scale that were relevant to physical forcing and ecosystem interactions.

Strictly speaking, carrying capacity refers to population parameters of a single species. However, it is useful to apply this concept to species groups. As a first approximation the function systems of the Subarctic Pacific into the following tentative grouping.

Phytoplankton:

Herbivores: Which includes micro–herbivores (e.g. ciliates), copepods, euphausiids, salps and some fish.

Small carnivores: Includes small fishes, zooplankton, squid, medusae, and arrow worms.

Large carnivores: Large fishes, large medusae, mammals and birds. Mobile organisms which can avoid adverse effects of physical forcing, but whose distribution may still be indirectly affected by forcing as it determines their prey distribution (Nekton). Juveniles may be members of lower trophic levels.

Table 3. Indices of Carrying Capacity. The fundamental assumption is that these indices will be compared as deviations from the mean ("anomalies").

	Small Scale	Mesoscale	Large Scale
Forcing	Ice Turbulence Internal waves Light penetration	Ice Mixed layer depth Convergence Eddies, jets Light Penetration Fronts, currents Fe input Variation in surface wind stress Species Composition	Ice Gyres, rings Fe input Light penetration Mixed layer depth Variation in surface wind stress (ENSO, Aleutian low, Kelvin wave trapped in coastal zone)
Phyto-plankton	Nutrient kinetics Photosynthetic kinetics	Size, chlorophyll concentration Primary productivity rates Nutrient concentrations Isotope rations (e.g., N-15) (Remote sensing (chlorophyll, etc.)	Remote sensing (chlorophyll, etc.)
Herbivores	Grazing thresholds Reproductive performance Patchiness	Condition index (fat content) Reproductive performance Productivity/Biomass Species composition Survival, size structure Biomass	Reproductive performance Growth rate Geographic distribution Survival, size structure
Small Carnivores	Foraging thresholds Reproductive performance Patchiness	Condition index (fat content) Reproductive performance Productivity/Biomass Species composition Survival, size structure Biomass	Growth rate, diet shift Reproductive performance Geographic distribution Survival, size structure Fish growth rates
Large Carnivores	Foraging thresholds Reproductive performance Patchiness Changes of foraging behavior	Condition index (fat content) Reproductive performance (e.g., fecundity, natality) Productivity/Biomass Species composition Survival, size structure Biomass, diet shift Changes of foraging behavior Reproductive success Geographic distribution	Condition index (fat content) Reproductive performance (e.g., fecundity, natality) Productivity/Biomass Species composition Survival, size structure Biomass, diet shift Changes of foraging behavior Reproductive success Geographic distribution
Ecosystem Interactions (competition, predation,etc)		Vertical flux of particles Ecological efficiency Size spectrum theory Species composition Predation rates (human vs other)	Vertical flux of particles Ecological efficiency Size spectrum theory Species composition Predation rates (human vs other)

Size spectrum theory

A potentially valuable conceptual framework to examine these interactions may come from the "size spectrum theory". This idea relates rates of productivity to the size class of the various organisms in the ecosystem. There are a number of important insights that are gained from this approach. Specifically, this approach could address how the ecological efficiency of a community changes as the productivity of the primary producers remains constant, while their relative body size shifts.

Fundamental to the study of species interactions is the need to develop models that can relate the various trophic levels and provide some integration. For this purpose it may be more instructive to select important indicator species for each trophic level that can be used to track these relationships described in Table 3. Ideally these species should have retrospective data sets available and sub–populations that exist within different regimes for comparative purposes.

Time Scale of Carrying Capacity Indices

Most of the indices presented in Table 3 can be measured using existing methodologies. Some data sets exist for various components in specific environments. Ideally, examination of carrying capacity would require simultaneous collection of these parameters over appropriate time periods. The importance of long time series to measure these parameters was emphasized in discussions. However, there are fiscal and logistical limitations. At the present time it is likely that GLOBEC would plan on time–series of 5–7 years. This is appropriate for measurements of quasi biennial oscillations (QBO) and annual fluctuations. However, short time series will not allow examination of interdecadal processes, regime shifts and lower frequency change. However, if a 5–7 yr– time series was acquired now, then a follow–on time series of 5–7 yr. could be used to examine these longer term processes. To resolve ENSO effects, we require a 15–35 year time series because the data record should be 3–5 times the period of the cycle of interest.

Determinants of Community Structure

A final aspect of the discussions was to address the issues of the importance of bottom up versus top down control of marine ecosystems.

The most powerful method of examining the factors that control community structure have been "removal" or "exclusion" experiments. One possibility is to examine human fisheries as a removal experiment. However, there are always the confounding variables of regime shifts and other physical features such as temperature. It would be interesting to examine fisheries removal within a given regime. As this may not be possible, the best approach to this problem would be to use models to examine ecosystem and community structure. A critical component of such models would include predation rates of both natural marine predators and humans.

Why questions on carrying capacity should be addressed

There are several reasons why the time is right to initiate studies to examine the impact of climate change on living resources. These include: 1) the existence of bio–physical models (see breakout session 4), 2) technology available to study on appropriate time and space scales (see breakout session 5), 3) PICES provides a comparative approach that would not be possible in a research effort launched by a single nation in a single region of North Pacific, and 4) measurements of ecosystem changes must be started as soon as possible to provide the necessary data for future generations of studies.

BREAKOUT SESSION 4—Modeling

What is required to model the impact of climate change on the carrying capacity of the region?

Discussion Leaders: Al Hermann and Bernard Megrey
Participants: Lou Botsford, Mike Foreman, Sarah Hinckley, Mike Landry, Jeff Parkhurst, Tom Powell, Michiyo Shima, Gordon Swartzman, Christina Tonitto, Anne York.

The concept of "carrying capacity" is difficult to define precisely in a modeling construct. The "carrying capacity" defined in the classic logistic model is inappropriate in many situations, since limits on population levels do not simply relate to resource levels, but can vary by life stage for many species, and often vary temporally (e.g., seasonally or from year to year). Moreover, this definition does not address multi–species assemblages and multi–species population dynamics. Factors controlling abundance other than resources include advection and predation.

Irrespective of precisely how carrying capacity is expressed in mathematical models, the following specific questions motivate bio–physical modeling efforts in the North Pacific.

1) Why is there no seasonal phytoplankton bloom in oceanic regions of the Subarctic North Pacific? What controls primary production and how might that change with any climate shift?

Programs other than the U.S. GLOBEC CCCC program are better equipped to answer these two questions. However, there is a strong need to link autotrophic production to higher trophic levels in bio–physical models of the area, a task for which a U.S. GLOBEC CCCC program is well suited.

2) What are the primary controls on fish productivity before predation occurs? Possibilities include food, offshore transport, and direct temperature effects. Responses to temperature shifts include vertical and horizontal migration of individuals.

3) How would migratory patterns change if climate alters circulation or hydrography of the environment?

4) How would the dominant species composition of the area change with any climate shift?

5) What accounts for the decline of pinnipeds in the far northern Pacific?

Both physical and biological scientists should be included in any modeling effort addressing such issues, to guide the development of the model in directions beneficial to both disciplines. A diversity of modeling approaches is more likely to be useful than any single approach.

Two reasons for this view are:

1) biological and physical questions to be explored with models are sometimes incompatible (e.g. different space and time scales);

2) ecological problems are difficult and complex, and no one modeling approach is clearly superior for all problems, or even for any single problem;

While recommendation of a single modeling approach is problematic, several characteristics may be identified as desirable attributes of modeling efforts directed at the issues above. a) Physics is best linked to biology by three-dimensional circulation models, driven by the most realistic wind and buoyancy forcing available. b) Lower trophic levels in particular should be linked to the physical forcing. c) Key species should be connected through multi-trophic level models. One reasonable approach is to choose focal species at each trophic level where good biological information is available, as a starting point for any model of the whole ecosystem. d) Models should include physiological and behavioral responses to the physical environment; this should be stage- specific, and where possible age and size specific as well. Animal behavior is especially important at higher trophic levels, but little information is currently available, especially regarding behavioral changes resulting from any climate shift.

Models could be nested: i) spatially, ii) temporally, and iii) trophically. Spatial nesting includes embedding of finer-scale regional models in coarser-scale, basin-wide or global models. This embedding allows the large–scale phenomena to impact the regional physics. Temporal nesting includes using time-averaged quantities from a short time-scale model in a long time scale model. More generally, one may use the results of a short time-scale model to aid parameterization of those processes which can not be modeled explicitly in the long time-scale model. This is akin to using fine grid circulation models to aid the development of better subgrid-scale mixing parameterizations in coarse grid circulation models. Trophic nesting refers to the use of detailed (e.g. multispecies) models within any particular trophic level of a highly aggregated, multi-trophic-level model.

Individual-based approaches are advantageous for some species; these may be coupled to hydrodynamic models for spatially explicit life histories. Advantages of the individual-based approach include its tracking of widely different life histories among individuals, which allows for a detailed analysis of successful individuals at the end of the simulation. One- dimensional Individual Based Models (IBMs) of phytoplankton have been developed, but may be difficult to implement in three dimensions. In the three-dimensional case, IBMs are more feasible (and have been developed) for species at higher trophic levels, where populations are typically smaller and more localized in space. IBMs of higher trophic levels may beneficially be coupled to more traditional, deterministic, Eulerian models of nutrients, phytoplankton, and zooplankton, especially when control of the plankton is primarily bottom-up rather than top-down. IBMs have also been combined successfully with more traditional age-structured population models.

Potentially IBMs could include a genetic component. Genetic drift may be important for species with short generation times (such as phytoplankton and zooplankton) when modeling decadal time scales. For species with longer generation times (such as fish), a presently rare genotype may become prominent following some catastrophic shift in climate; for example, rapid environmental change might confer an advantage on individuals with a particular behavioral strategy, while others suffer disastrous mortality. Genetic/behavioral tagging of individuals in an individual-based model is one way of exploring such possibilities.

Bio–physical models, like their purely physical counterparts, can ultimately benefit from the assimilation of Eulerian and Lagrangian data, especially when such models are used for hindcasts. Such bio–physical assimilation is feasible with current technology. Data which could be assimilated into bio–physical hindcasts of the northern North Pacific include moored current meter and bio-optical data, altimeter data, drogued drifter data, and fish surveys. Techniques for assimilation range from simple "nudging" of the model variables towards observed values (a primitive form of Kalman filtering), to sophisticated adjoint techniques which effectively minimize the difference between observed and modeled values by repeated adjustment of initial conditions, boundary conditions, and parameters of the governing equations. Nudging is easily implemented even in a three dimensional context (and is done currently in several primitive equation models of ocean circulation). The more sophisticated techniques are preferable in theory but computationally intensive. In practice, they have been employed mainly in one- and two-dimensional contexts, with linearized physical models. Implementations with more complex, bio–physical models are being developed by several researchers, however.

While the formulation of governing equations and choice of parameters in a bio–physical model is not trivial, reasonable choices can be made, and results of coupled bio–physical models in other areas of the world (such as the North Atlantic) have been encouraging.

A review of past, ongoing and planned physical modeling efforts is presented here for the Gulf of Alaska and Bering Sea areas. Output from eddy-resolving models with global coverage may be useful in setting boundary conditions for regional scale simulations of the Gulf of Alaska or the Bering Sea; hence both global (but eddy-resolving) and regional models are included in this summary. Many of the basin-scale and regional models are likewise eddy resolving, with horizontal grid spacing on the order of 20 km or finer.

Physical models of the Gulf of Alaska have been broadly classed here into: 1) global eddy-resolving models which include the Gulf, 2) North Pacific models which include the Gulf, and 3) coastal models of subregions of the Gulf (Table 4). The class of basin-scale models may be subdivided according to the governing equations as: 1) quasigeostrophic or 2) primitive equation. For coastal models we distinguish between 1) tidal models, which replicate tidally driven, but not wind- or buoyancy-driven currents, and 2) primitive equation and other wind and/or buoyancy driven models. Also included are hydrologic models and inverse models of currents, temperature and salinity in the Gulf.

A related classification scheme has been used to illustrate modeling efforts in the Bering Sea (Table 5). We distinguish among: 1) global eddy- resolving primitive equation models which include the Bering Sea, 2) North Pacific models which include the Bering Sea, and models which focus on the entire Bering Sea basin (though some exclude the shelf area), 3) models on the Northern Bering Sea and Bering Strait, 4) models of the Southeastern Bering Sea shelf, 5) models of sea ice in the Bering Sea, 6) inverse models of circulation and other properties in regions of the Bering Sea.

Table 4. Varieties of physical models for the Gulf of Alaska. ERPE=Eddy Resolving Primitive Equation Model; Layer=Layer model (divides the water column into discrete layers of uniform density); QG=Quasigeostrophic model; PE=Primitive Equation

Domain: **Type:**	**Global** **ERPE**	**Basin** **Layer**
	Semtner and Chervin (1992)	Hurlburt et al. (1992)
	Smith, Dukowicz and Malone (LANL)	Heim et al. (1992)
	Japanese Meteor. Agency (JMA)	Yamanaka and Kitamura (Met.Res.Inst.,JMA)
	Melsom et al. (submitted)	

Domain: **Type:**	**Basin** **QG**	**Basin** **ERPE and other**
	Cummins (1989)	Hsieh and Lee (1989)
	Cummins and Mysak (1988)	Lee et al. (1992)
	Cummins and Freeland (1993)	Haidvogel et al. (Rutgers)
	Jiang et al. (1995)	Yamagata (Tokyo Univ.)
		Ingraham and Miyahara (1988)
		Ingraham et al. (1991)
		Yoshioka and Yoon (1992)

Domain: **Type:**	**Coastal** **Tidal**	**Coastal** **PE and other**
	Liu and Leendertse (1990)	Johnson (MMS)
	Bang (KORDI)	Hermann and Stabeno (1996)
	Kowalik (UAF)	Barth (1995)
	Foreman et al. (1993)	Allen (UBC)
		Walters and Foreman (1992)
		Foreman et al. (1992)
		Hannah et al. (1991)

Type:	**Inverse**	**Hydrologic**
	Matear (1993)	Royer (1982)
	Kowalik et al. (1994)	

Abbreviations: JMA—Japanese Meteorological Agency; KORDI—Korean Ocean Research and Development Institute; LANL—Los Alamos National Laboratory; UAF—University of Alaska Fairbanks; UBC—University of British Columbia

Table 5. Physical models of the Bering Sea.

Domain:	Global	NP and Bering Sea
	Semtner and Chervin (1992)	Hurlburt et al. (1992)
	Smith, Dukowicz and Malone (LANL)	Haidvogel et al. (Rutgers)
	Yamanaka and Kitamura (Met.Res.Inst.,JMA)	Yoshioka and Yoon (1992)
	Overland et al. (1994)	
	Han and Galt (1979)	
	Hedstrom and Haidvogel (Rutgers)	
	Ingraham and Miyahara (1988)	
Domain:	**QG**	**ERPE and other**
	Overland and Roach (1987)	Liu and Leendertse (1990)
	Spaulding et al. (1987)	Walsh and McRoy ((1986)
	Spaulding (1988)	Overland (PMEL)
	Shuert and Walsh (1992)	Hermann et al. (UW)
	Nihoul et al. (1989)	
	Nihoul et al. (1993)	
Type:	**Ice**	**Inverse**
	Overland and Pease (1988)	Nihoul et al. (1993)
	Pease (PMEL)	Brasseur (1991)
	Kantha and Mellor (1989)	Brasseur and Haus (1991)

Abbreviations: JMA—Japanese Meteorological Agency; LANL—Los Alamos National Laboratory; PMEL—Pacific Marine Environmental Lab.; UW—University of Washington

BREAKOUT SESSION 5—Technology

What are the technological impediments to measuring the effects of climate change on the carrying capacity?

Discussion Leaders: E. D. Cokelet and Hal Batchelder
Participants: Paul Bentzen, Jim Larsen, Richard Merrick, Richard Methot, Jeff Napp, Ian Perry, Jim Traynor

The mission of this working group was to address the question shown above. Advantage was taken of the small–group format to discuss climate change and carrying capacity in more general terms as well.

Climate Change and Carrying Capacity

Climate change means the large–scale, long–term change in atmospheric and oceanic forcing and its effect on the oceanic ecosystem. Change could manifest itself as a trend, a regime shift—an abrupt change in the mean of some climatic time series—or as a change in the variability. As an example of the last type, an enhanced horizontal temperature gradient across a nonstationary front would lead to increased temperature variability as the front moved back and forth. Such a change may not initially be recognized as a climate change, but instead be interpreted as a change in the spatial distribution of ocean processes. Another example might be the change in the frequency and intensity of winter storm winds, with no accompanying overall change in the mean winter wind vector.

The carrying capacity of a biological population, measured in terms of the number of individuals or biomass, is the asymptotic upper limit that is controlled by population density or equivalently resource limitation (Odum, 1971). It may be determined by the availability of food, space or some other aspect of the system. For a hypothetical example of climate change affecting carrying capacity, consider a species whose territorial range shrinks because it cannot tolerate warmer water caused by global warming. As the population is forced into a smaller geographical area, its density will increase perhaps until its needs exceed some resource, e.g. food supply or breeding substrate. Then its numbers will decrease, asymptotically approaching or oscillating about a new, lower carrying capacity.

Human intervention may displace commercial fish stocks from their carrying capacity level. To increase fishery yield, walleye pollock (*Theragra chalcogramma*) are managed at about one–third of their pre–exploitation biomass, which might be their carrying capacity. In contrast, hatchery reared juvenile salmon introduced into their natural habitat (e.g. the North Pacific) may increase their population to levels above their carrying capacity. Compensatory poor growth and high mortality may result.

Variability, Process Studies vs. Monitoring and Pulse Points

Since by definition climate change is a large-scale, long-term process, the study of its effects usually requires that ample measurements be made over a large geographical area with long duration. This is illustrated in the work of Brodeur and Ware (1992) who observed a two–fold increase in the zooplankton biomass of the eastern Subarctic Pacific from the late 1950's to the 1980's. Their results are significant only when averaged over several cruises and years given that biomass estimates from replicate zooplankton tows at one station can differ by 100% . In general, the minimum observation time necessary to discern a long-term trend in the presence of short-term variability is approximately twice the ratio of the square root of the variance to the trend. The purpose of geographical averaging is to reduce the variance and to increase the areal relevance.

The following table provides a comparison of two types of complementary studies that are applicable to our research problem: 1) process studies, and 2) continuous, long–term measurements, i.e., monitoring.

Table 6. Process studies vs. monitoring

Process Studies	**Monitoring**
Lead to understanding of mechanisms	Leads to recognition of change, regime shifts
Relate cause to effect	Correlate changes
Smaller scale, shorter duration	Larger scale, longer duration
Best conducted at representative sites	Best conducted at pulse points
Harder to link to climate	Easier to link to climate
Easier to link to carrying capacity	Harder to link to carrying capacity

Detailed process studies are better suited to increase the understanding of a phenomenon through studying cause–and–effect linkages, for example relating food supply to carrying capacity. Larger–scale, longer–term monitoring is better suited for observing variability correlated over space and time, e.g. climate change. One problem with trying to deduce climate effects from a process study is that an agent that may dominate on the short time scale may play little role over the longer term. Roemmich and McGowan (1995) found that the slow decline of zooplankton population abundance over 43 years in the California Current could not be extrapolated from monthly or seasonal balances.

The Subarctic Pacific and Bering Sea vary seasonally and occupy such a vast area that they could not be sampled often and finely enough by a typical five–to–seven–year PICES/GLOBEC research program. Therefore a **major challenge** is to choose appropriate variables to measure at key or **pulse points** where the short period variance is minimized and the effects of climate change on carrying capacity are indicative of large–scale changes.

The Kamchatka Current might be a pulse point for the circulation in the Bering Sea. Although inflow to the Bering Sea from the Alaskan Stream occurs through several Aleutian passes, outflow is predominantly through Kamchatka Strait (Fig. 2) in a narrow, strong current. Thus the outflow should be a good indicator of the mean cyclonic circulation for the entire basin. Moreover, the strength of the outflow from the Bering Sea in the Kamchatka Current is related to the location and strength of the Aleutian Low, the primary atmospheric forcing in this part of the ocean (Bond et al., 1994). The Alaskan Stream might be a similar pulse point for the Gulf of

Alaska gyre. It is stable west of Kodiak Island to the dateline and represents part of the return flow from the northern branch of the bifurcated West Wind Drift. Chelton and Davis (1982) have hypothesized that changes in the north/south apportionment of the West Wind Drift as it nears the North American continent affect the eastern North Pacific circulation and the biomass of zooplankton in various oceanic subregions.

Technologies

A variety of technological issues were discussed during the breakout session. Recent publications by U.S. GLOBEC provide useful overviews of emerging and desired technologies. They will be reviewed briefly here and can be consulted for further details.

GLOBEC Report 3 (U.S. GLOBEC, 1991a) discussed the application of biotechnology to zooplankton field studies. Biochemical and molecular techniques exist to determine physiological rates and condition and are beginning to be applied in the marine environment. Feeding rates and dietary composition might be investigated using DNA probes and immunological and pigment identification of prey species. The possibility of using zooplankton genetics for automated real–time plankton sorting is low, but should be encouraged. Genetics can be used to identify and characterize zooplankton populations and perhaps to sense adaptation to global climate change.

A 1991 U.S. GLOBEC workshop (U.S. GLOBEC, 1991b) dealt with the existing capabilities and potential developments in acoustical and optical technology, methodology and instrumentation for measuring the distributions and assessing the behavior of marine animals. Sensors are needed that operate on continuous temporal and spatial scales in order to couple small–scale physical processes to population parameters. Acoustical and optical measurements should be integrated. Physical and biological observations in the water column should be synoptic rather than serial. It was recognized that data definition, organization, archiving, access, retrieval and display were important issues for GLOBEC. A modular acoustical instrument design approach was suggested so that common parts and algorithms could be shared as much as possible to construct instruments with different frequencies and beamwidths to measure the many size classes from zooplankton to fish. A recommendation was made for new research to advance the theory and measurements of scattering from individual organisms.

The U.S. GLOBEC Optics Technology Workshop (U.S. GLOBEC, 1993) focused on the potential to determine biomass and rate processes of zooplankton *in situ*. Optics with its fine resolution but limited effective range is best used on scales of microns to meters. Optics and acoustics complement one another. For example, optics can identify taxa, and acoustics can quantify size distributions. Two- and three-dimensional, non-intrusive observations should lead to a better understanding of feeding, swimming and predation rates. Optics can also be applied to quantify the distribution, abundance and types of zooplankton prey.

Two other GLOBEC publications refer to technology. Most issues of the *U.S. GLOBEC News* contain a Technology Forum that deals with new instruments. A section of the California Current Workshop report also (U.S. GLOBEC, 1992) considers the special technological needs of that program.

The table below lists the technologies we discussed and describes some of their advantages and disadvantages. Although computational modeling could be considered a technology, it was the subject of another breakout session and was not considered here.

Four specific technological impediments emerged that are relevant to this PICES/GLOBEC initiative.

1. Salinity measurements from satellites—Satellites provide a platform to measure sea–surface temperature on large scales during cloud–free conditions, but in the area of concern, temperature has less dynamical influence than in the tropics. Owing to large freshwater inputs, salinity governs density more than temperature in the Gulf of Alaska and Bering Sea. Efforts to measure salinity from satellites should be encouraged (Lagerloef et al. 1995).

2. Oceanic transports from submarine cable voltage measurements—Electro–magnetic observations from both abandoned and active submarine telephone cables have been used successfully to measure the transport in the Florida Current on a day–to–day basis (Larsen, 1992). These provide a level of temporal resolution and spatial averaging unsurpassed by any other technique. Cables installed (or already present) at several key "pulse" points might be invaluable for describing large–scale temporal variations in ocean transport. Likely candidates for monitoring are the Alaskan Stream, Kamchatka Current, and perhaps the California Current.

3. Medusae sampling—The ecological importance of medusae in the North Pacific and Bering Sea is unknown but could be large. They may be a significant predator and competitor to various life stages of fish, and the biomass locked up in jellyfish may not be available to fish and higher trophic levels. They are difficult to sample because they disintegrate in plankton nets. Methods need to be developed to determine medusae abundance and feeding habits and rates rapidly over relatively large areas to evaluate their importance and impact on the North Pacific ecosystem.

4. Measurements of ocean temperature over large areas—The ATOC (Acoustic Thermography of the Ocean Climate) program currently planned to run from December 1995 to September 1996 may provide information that will improve our measurements of ocean temperature over large areas. This project will provide daily measurements of mean ocean temperature across large sections of the North Pacific. Temperature measurements are taken by measuring the velocity of sound as it traverses the ocean. Data derived from these experiments could provide insight into long term variations in the thermal budget of the ocean.

Table 7. Technologies

TECHNOLOGY	ADVANTAGES	DISADVANTAGES
Research Vessels	Most flexible platform available. Variety of measurements possible.	Expensive. Cannot provide synoptic coverage easily.
Ships of Opportunity	Potential wide spatial and frequent temporal coverage. Inexpensive.	Difficult logistics. Quality control problems.
Aircraft	Good spatial coverage in selected regions.	Expensive. Limited by weather. Limited instrument types and numbers Focus on near–surface observations.
Satellites	Synoptic, good spatial coverage, reasonably good temporal resolution. Low operating costs. Good for sea–level, temperature, pigments and winds.	High initial cost. Long–term stability in question. Clouds cause problems. Some sensors not useful near shore (within 50 km). Limited to near–surface conditions.
Moorings	High temporal resolution. Capable of handling many different types of sensors incl. physical, bio–optical, acoustical, meteorological.	Low spatial resolution except in the vertical dimension. High cost. Difficult to maintain on fishing grounds.
Drifters	Follow water mass (Lagrangian). Can provide ancillary physical and bio–optical data.	Potential for instrument loss. High cost for heavily instrumented versions.
E–M Cable Voltages	Low operating cost. Low maintenance. Provide estimates of spatially integrated transport. Good for long–term sampling.	High initial cost if new cable required. Difficult to use in regions with fishery operations. Calibration required.
Acoustics	Mature technology with many different sensor options. Measure abundance, size–frequency distribution and currents (ADCP). High vertical resolution.	Rarely provide species identification. Boundary interference.

Optics	Various technologies of varying capability available including Video Plankton Recorder (VPR), Optical Plankton Counter (OPC), absorption meters, Lidar. Some can provide taxa identification. Some can be deployed on moorings or drifters. Can estimate standing stock of autotrophs and small heterotrophs.	More advanced systems, such as VPR are not mature, not readily available and not cheap. Less expensive technologies (OPC) provide size structure, but not taxa identification. Short range.
Molecular and Biochemical Methods	Can be used to evaluate physiological condition, diet, stock structure, species identification and perhaps age of target organisms.	Development of techniques. Labor intensive, but potential for automation and use of robotics.
Historical Proxies	Tree rings, sediment cores, cold water corals, forams and isotopic scale analysis might provide time–series records of atmosphere, ocean or ecosystem conditions.	Lots of exploratory work needed. Calibration of some techniques difficult. Provide no recent information.
Smart Tags	Can be used to describe animal behavior, geographic position, migration patterns, and monitor physiological condition. Already proven useful for some fish and many marine mammals.	Potentially low return rates. Need to keep the tags inexpensive. Only applicable to larger organisms.

BREAKOUT SESSION 6—Spatial and Temporal Scales

What are the spatial and temporal scales required to re–solve questions concerning climate change and carrying capacity?

Discussion Leaders: Robert Francis and Warren Wooster
Participants: Bud Antonelis, Ted Cooney, Michael Dahlberg, Art Kendall, Kate Myers, Charles Miller, Phyllis Stabeno, Vidar Wespestad.

Spatial scales

Presumably the spatial scale of climate forcing is large, basin scale at least, encompassing the equatorial Pacific (as it relates to ENSO) as well as the system of highs and lows ex–tending from Siberia to the west coast of North America. Variations in the atmospheric pressure field are manifested through variations in air/sea heat and momentum exchange, both of comparable large scale. The surface layer of the ocean responds on similar and smaller scales, for example the mesoscale features of eddies, convergences and divergences, etc. Vertically, the scale of surface layer thickness, of the order of 100 meters, is particularly important.

Ecosystem scales appear to be smaller than those of climate forcing. However, if the climate forcing manifests itself as Rossby waves or as poleward displacements of boundaries then they would be of similar scale. The ecosystems of interest here are the Gulf of Alaska, the eastern Subarctic gyre, and the eastern Bering Sea shelf. In considering the carrying capacity for salmonids in the Subarctic Pacific, the dimension of the Subarctic gyres (i.e., the oceanic pasture) determine an important scale.

Even smaller systems can be defined, e.g., Puget Sound or Prince William Sound. These interact with larger scales and may serve as microcosms for study of processes that typify the larger systems. Process studies may encompass scales from that of the ecosystem to that of plankton patches or even to the ambit of individual plankters.

Temporal scales

While seasonal scales dominate life histories, longer time scales are more relevant in considering the climate forcing of ecosystems. Much attention has been paid to interannual variability, but in the case of climate fluctuations, decadal and longer scales seem to be more important and to have more identifiable patterns. There has been particular interest in the regime shift scale, of the order of decades. Note that, atmospheric changes may be more rapid than those in the ocean due to the greater heat capacity of the ocean, and lags between forcing and response may differ from region to region.

Time scales of ecosystem response are less clear. Seasonal, interannual, and decadal scales are all evident. Different trophic levels and key species have different response times and scales. Little is known about the time scale of changes in carrying capacity for high level carnivores, which may be on the regime shift scale or longer. High level carnivores like marine mammals and seabirds are long lived species that must be able to withstand annual and decadal variations in food resources over large spatial and temporal scales. During the breeding season birds and fur seals have a limited foraging range since they must return to feed their young waiting onshore. Breeding sites are therefore limited to islands or continental regions with a oceanographic regime that ensures an abundant and predictable supply of food throughout the breeding season. Furthermore, since these animals are long lived and show high degrees of site fidelity, resource availability must be reliable over time scales of many years to decades.

Conclusions

1) There is a continuum of spatial and temporal scales of concern to the program. Criteria for selecting specific scales are: (1) those where important variability is concentrated, (2) those that relate to plausible mechanisms of interaction, and (3) those that relate to applied problems.

Existing historical data, such as CalCOFI, Ocean Station P, GAK1, FOCI line 8 and PROBES lines, are extremely valuable time series and should be considered by those contemplating new sampling programs.

2) The comparison of events in different regions and at different times is a powerful approach which can be facilitated by PICES. Comparisons between the eastern and western Bering Sea and Subarctic Pacific are likely to be particularly fruitful. An important PICES contribution can be to make data from the western Subarctic Pacific more accessible.

3) From an ecosystem point of view, there are species (or groups) that have been consistently missing in ecosystem analyses. These include forage fish species, jellyfish, and top carnivores such as marine mammals, seabirds and humans (which are a major component of top–down forcing).

4) Relatively short time scales are amenable to direct study whereas decadal and longer scales can only be studied through retrospection and modeling.

5) An important question is how different species respond to climatic forcing at different frequencies.

COASTAL GULF OF ALASKA BREAKOUT SESSION

Discussion Leaders: Tom Royer and Anne Hollowed
Participants: Tim Baumgartner, Louis Botsford, Dan Cayan, Ted Cooney, Mike Dahlberg, Robert DeLong, Robert Francis, Nick Graham, Robert Haney, Scott Hatch, Al Hermann, Sarah Hinckley, Steve Ignell, Art Kendall, Allen Macklin, Nate Mantua, Richard Methot, Brenda Norcross, Ian Perry, Pete Rand, Michiyo Shima, Ted Strub, Dan Ware

Introduction

The coastal Gulf of Alaska (GOA) supports a complex ecosystem that includes a variety of commercially important marine resources including crab, shrimp, salmon and walleye pollock (Anon. 1993). The coastal GOA ecosystem appears to be sensitive to climate variability on time scales of several years to decades. The mix of higher trophic level species appears to have changed during the late 1970s, coincident with a major change in ocean conditions. Commercial catch for shrimp and crab declined, while many groundfish and salmon populations increased (Albers and Anderson 1985, Blau 1986, Hollowed et al 1994, Thompson and Zenger 1994, Francis and Hare 1994) . Abundance of several top trophic level predators declined in the region in the 1980s (Merrick et. al. 1987, Hatch and Sanger 1992). One of these, the Steller sea lion, is currently listed as a threatened species under the Endangered Species Act. While these changes appear to coincide with major shifts in ocean conditions, comprehensive investigations of the ecosystem response have not been conducted.

The bathymetry of the coastal GOA provides a contrast between a broad shelf region in the central and western Gulf and a narrow fjord like region off Southeast Alaska and British Columbia. The shelf is punctured by submarine canyons and frequent bays, sounds and inlets including: Yakutat Bay, Prince William Sound and Cook Inlet (Figure 3).

The major oceanographic features of the Gulf of Alaska include mesoscale eddies, strong coastal currents adjacent to a major oceanic current system, and frequent storm activity. The Shelikof Strait region supports mesoscale eddies which appear to be important for survival of larval walleye pollock (Schumacher et al., 1993; Bograd et al. 1994). The Alaska Coastal Current (ACC) is the dominant current on the shelf and is characterized as a narrow (<25 km), low salinity current driven by wind stress and freshwater input from sources along the coast (Royer 1981) (Figure 1). The Alaskan Stream current is south of the Alaska Peninsula and marks the northern boundary of the Pacific subarctic gyre (Reed and Stabeno 1993) (Figure 1). The flow of water in Shelikof Strait is composed of a two–layer, estuarine-like circulation with more saline slope water entering the sea valley in the bottom layer and ACC waters in the upper 150 m (Reed 1987).

Breakout Discussions

The coastal GOA breakout group began discussions by identifying key questions regarding three subject areas: physical forcing, lower trophic level response, and higher trophic level response. The key questions suggested by the group are outlined below. Following these discussions, the group identified potential research projects to address the key questions through retrospective studies, monitoring and modeling. While process oriented studies are considered a crucial part of a U.S. GLOBEC activity time did not permit consideration of this type of research.

Physical Questions

1. How do changes in atmospheric forcing influence coastal circulation in the GOA?
2. How do the Alaskan Stream and the Alaska Coastal currents interact?
3. How do changes in precipitation and freshwater runoff influence coastal circulation in the GOA?
4. What is the role of bottom topography in determining coastal circulation in the GOA?
5. What is the role of tides in controlling nutrient flux in the GOA?
6. How do the factors identified above influence the: mixed layer depth (MLD), mixed layer temperature (MLT), retention time–scales (eddies), turbidity, cross shelf transport?

Lower Trophic Level Questions

1. What factors control primary production in the coastal Gulf of Alaska? Issues of interest include: light/nutrient/prey concentration and availability; species mix, prey quality (i.e. biochemical composition, as relates to essential amino and fatty acids).
2. How do the above changes in transport processes (vertical and horizontal, along shore and cross shelf) due to climate variability influence the composition and production of coastal plankton communities?
3. Is grazing/predation a major factor structuring plankton communities in this region?
4. How would climate induced changes in the mixed layer depth (MLD) influence production at lower trophic levels?
5. How might climate change influence trophic phasing in the coastal GOA?
   Close coupling favors pelagic food webs
   Decoupling favors demersal or benthic food webs
6. How would climate change influence over-wintering plankton communities and biomass – i.e. as a baseline for the following spring bloom?
7. How would changes in precipitation and runoff (pattern, timing, magnitude) influence plankton communities in the GOA - either directly, or indirectly through changes in circulation?

Higher Trophic Level Questions

1. How do changes in climate affect the distribution of predators; large scale and locally; vertically and horizontally? More specifically questions might include the following. Do physical oceanographic processes affect or possibly determine the dynamics of prey patches? Is physical forcing important in aggregating prey and making them available for efficient predation? How are these features effected by climate variability.

2. How does climate change influence prey abundance and what role does it play in determining growth, survival and reproduction of higher trophic level species?
   • Coastal Plankton

    • Forage Fish

3. What are the benefits of adjusting marine resource policy to track climate induced changes in marine production?
4. How do marine organisms respond to rapid and large–scale climate changes (e.g. regime shifts)?
    • Behavior
    • Physiology
    • Genetics
5. How might climate change alter the composition of fish communities?
6. How would climate change effect the seasonality of resources available to apex consumers?

Retrospective Studies

Several data sets and their sources were identified that could be used to conduct retrospective studies of the Gulf of Alaska ecosystem (Table 8). The group also identified several types of retrospective analyses that could be conducted to address the questions above. These retrospective questions are not listed in order of priority and should not be considered the only types of retrospective questions that could be addressed in the region.

Recommended retrospective analyses regarding forcing questions

1. Compare time series of coastal meteorology station data, atmospheric pressure data and current measurements made at GAK1 and FOCI line 8 to examine the impact of atmospheric forcing on coastal circulation (addresses physical question 1) .
2. Compare time series of precipitation, runoff, and NODC temperature and salinity profiles with current measurements from GAK1 and FOCI line 8 to measure the influence of freshwater on coastal circulation (addresses physical question 3).
3. Conduct spatial analysis of NMFS and NODC temperature and salinity profiles, ships of opportunity data, and remote sensing data to identify major physical features and to map their spatial and temporal patterns (addresses physical question 6).
4. Compare time series of nutrient concentrations from stations in the eastern and western Gulf of Alaska for evidence of differences in nutrient flux. Examine the data for evidence of tidal influences (addresses physical question 5).
5. Construct time series of mixed layer depth, mixed layer temperature, eddies (retention), turbidity, and cross-shelf transport and conduct simulation studies and multivariate analyses to explore potential relationships of these times series to atmospheric and large scale climate variability (addresses physical question 6).

Recommended retrospective analyses regarding lower trophic level response questions

1. Analyze species composition of existing zooplankton samples from three regions of the Gulf of Alaska: Southeast Alaska or La Perouse Bank {although note that La Perouse Bank is more representative of the California Upwelling domain} , Prince William Sound, and Shelikof Strait. Compare indices of mixed layer transport (vertical and horizontal, along shore and cross shelf) with time series of species composition and production of coastal plankton communities.

2. Compare time series of physical variables such as the mixed layer depth, precipitation or runoff with time series of plankton abundance identified by taxonomic group or species.

Recommended retrospective analyses regarding higher trophic level and ecosystem response questions

1. Conduct spatial analyses of the distribution of predators, identify major oceanographic features that influence the distributions of higher trophic level predators and their prey.
2. Conduct multivariate analyses of time series of physical oceanographic, atmospheric and recruitment (survival indices) of higher trophic level species.
3. Examine historical information on the growth of higher trophic level species and compare historical information with indices of climate variability and prey abundance.
4. Conduct simulations to explore the impact of adjusting marine resource policy to track climate induced changes in marine production
5. Identify how organisms adapt to a new environment and how successful the adaptation strategy is for survival in a new regime.
6. Construct a simulation model using past climate trends and potential climate change effects on the seasonality of resources available to apex consumers and compare the results against observed distributions and abundance.

Potential Monitoring Activities

This group discussed several types of monitoring activities that would be useful in a U.S. GLOBEC program in the Gulf of Alaska (Table 9). These included existing and proposed monitoring activities. For example, the group recommended that volunteer ships and the Alaskan Ferries could provide valuable physical, chemical and biological samples if they were properly equipped. Several pulse points were identified where attempts should be made to initiate, continue, reinstate or expand monitoring activities: FOCI line 8, GAK1, line P, and the flow through Unimak Pass.

Recommendations for Future Modeling

There are modeling activities on–going for various regions of the Gulf of Alaska, most notably in Shelikof Strait and the Western Gulf of Alaska, Prince William Sound, and La Perouse Bank (although the latter more correctly represents an upstream boundary for the Gulf of Alaska System). Modeling activities need to integrate physical and biological responses (from physical forcing to lower to higher trophic levels) to climate–induced variability in along–and cross-shelf circulation, to vertical mixing processes, and to variations in upstream conditions—e.g., variations in the intensity and location of the North Pacific Current and its bifurcation at the coast of North America.

An effort to nest regional models of Shelikof Strait, Prince William Sound, and Southeast Alaska into a large-scale bio–physical model of the Gulf was recommended. Existing output from large-scale physical simulations of the North Pacific might be employed for this purpose, serving as boundary conditions on the regional models. True nesting, with feedback from the regional to the larger scale model, is preferable, but one-way coupling could be fruitful for comparing regional responses to large-scale climate change. If such a modeling exercise was undertaken the physical model should have some mixed layer physics, to get the lower trophic levels adequately. Existing physical model output could be used to drive a suitable biological model. A broad-scale biological model of the Gulf might include the following: phytoplankton and protozoa, euphausiids and copepods, jellyfish, salmon, herring, and pollock.

OCEANIC SUBARCTIC BREAKOUT SESSION

Discussion Leaders: William Pearcy and Warren Wooster
Participants: Bud Antonelis, Karl Banse, Richard Beamish, George Boehlert, Nick Bond, Michael Foreman, Bruce Frost, Steve Hare, James Ingraham, Charles Miller, Jeff Parkhurst, Timothy Parsons, William Peterson, Ron Thom, Cynthia Tynan

Introduction

The Science Plan for the PICES-GLOBEC Program on Climate Change and Carrying Capacity (CCCC) gives high priority to basin scale studies "*to determine how plankton productivity and the carrying capacity for high trophic level, pelagic carnivores in the North Pacific change in response to climate variations.*" A later PICES document "On the development of an implementation plan" identifies the western and eastern Subarctic gyres as the focus of international basin scale studies in the CCCC Program. Some of the reasons for developing an Oceanic Subarctic component follow.

The oceanic Subarctic Pacific Ocean, including all waters north of the Subarctic Boundary, is a large, productive and relatively simple ecosystem. It experiences large seasonal, interannual and decadal changes in upper ocean physics that are apparently linked to the biology of organisms. Despite the correlations between physics and biology, our understanding is limited about processes actually affecting productivity and distribution of animals (see however Miller et al. 1991; Miller 1993).

The climate of the Subarctic North Pacific Ocean changed during the late 1970s. In response to this climate change, the Aleutian Low intensified (Trenberth and Hurrell 1994); sea surface temperatures rose rapidly by several degrees (Rogers and Ruggerone 1993; Royer 1989; Graham 1995); zooplankton biomass and the catches of epipelagic nekton increased (Brodeur and Ware 1992; 1995). Salmon catches from the North Pacific increased sharply, especially in Alaska, and exceeded historical levels (Pearcy 1992; Beamish and Bouillon 1993; Francis and Hare 1994).

During this recent period of high fish production, evidence accumulated that several species of salmon, of both North American and Asian stocks, were returning as mature or maturing fish at increasingly smaller sizes (Kaeriyama 1989; Ishida et al. 1993; PICES 1993). This suggests density-dependent growth and competition for food in the ocean. Apparently, the carrying capacity of the Subarctic Pacific for salmonids, a major group of epipelagic fishes, was exceeded, even during this period of exceptionally favorable ocean conditions of the 1980s and 1990s. If the next climate shift is to cooler and less productive conditions, this problem will be exacerbated and have major economic consequences for nations along the Pacific Rim that produce wild and hatchery salmon (PICES 1993).

Besides changes in the productivity per unit area, global warming may also reduce the geographic area that is optimal for salmon growth and survival. Recent observations by Welch et al. (in prep.) suggest that salmon may undertake a reverse, northward migration during the winter. If this is true, and if global warming continues, the area of suitable habitat for salmon could be severely restricted during that season.

These pronounced large-scale climate fluctuations in the Subarctic Pacific, and their societal importance, are cogent reasons to improve our understanding of the linkages between physical and biological processes of this region.

There are other scientific reasons for expanding our research in the Subarctic Pacific. Strong physical and biological interactions occur on both seasonal and interannual time scales. Variations in the strength of the Aleutian Low result in large seasonal changes in atmospheric forcing (Wilson and Overland 1987). However, no phytoplankton bloom occurs during the spring. Is this because of lack of iron, grazing by microzooplankton or both(Miller et al. 1991)? Every spring and summer, a huge biomass of epipelagic fishes, such as Pacific pomfret and Pacific saury, migrates across the Subarctic Boundary into the Subarctic Pacific to feed (Neave and Hanavan 1960; Taniguchi 1981). What are the impacts of these seasonal migrants on the food web structure that includes salmonids? Interannually, variations in the standing stocks of zooplankton are correlated with the intensity of winter winds (Brodeur and Ware 1992), but is this related to Ekman pumping and production or changes in the structure of the food web? The details of these physical–biological processes are lacking.

Moreover, excellent background information about the Subarctic Pacific is available. This will facilitate retrospective studies of climate change and formulation of hypotheses relating physical and biological processes. Previous studies include the long time- series of physical and biological measurements at Ocean Station "P" (Fulton 1983; Frost 1983), the SUPER Project (Miller 1993), ecosystem modeling (Frost 1993), a 25 year hydrographic time series at Seward, Alaska (GAK1), and repeated biological and oceanographic measurements in conjunction with cruises by the International North Pacific Fisheries Commission and Hokkaido University. In addition, a long history of catch records is available, as are collections of salmon scales to provide long-term comparisons of ocean growth.

Breakout Discussions

In considering the development of an Oceanic Subarctic component of the PICES-GLOBEC CCCC Program, the group accepted the four PICES Central Issues (see page 1) as a basis for discussion. However, it was noted that whereas emphasis was given to the regime shift scale in the questions, studies related to Climate Change and Carrying Capacity would as well have to be carried out at seasonal, interannual, and interdecadal scales. In general, the longer scales would only be accessible through retrospective studies. The role of humans should not be ignored.

The approach followed was to examine a matrix of questions and research approaches:

Question	**Retrospection**	**Model**	**Process Study**	**Observation**
Physical Forcing				
Lower T.L				
Higher T.L.				
Ecosystem Interactions				

A summary of information in the matrix cells is discussed below.

The group then broke into three subgroups with the charge to identify the most promising questions for early development and implementations. The subgroups were physical forcing/lower trophic levels, higher trophic levels, and ecosystem interactions.

In the case of retrospective studies, the longest time series are for certain atmospheric conditions (air temperature, sea level pressure) which permit a general description of climate variations. Fewer data concerning abiotic conditions are available from the ocean, and even fewer for the lower trophic levels. Higher trophic level data come mostly from fishery statistics which extend back about 100 years for some North Pacific species. Cores of anoxic sediments in British Columbia and the Aleutian Islands may also provide long time series for retrospective studies of changes in fish communities. Historical data on ecosystem interactions is limited because it is dependent on information from both lower and higher trophic levels.

Whereas, modeling and process studies differ among trophic levels, there are some measurements that are required for all levels. Monitoring can be carried out from moorings, ships (especially Volunteer Observing Ships, VOS), drifters, and satellites, each being preferable for one or another type of observation.

However, it does seem desirable that a monitoring program be developed that maximizes the suite of measurements that will be made.

Reports of subgroups

Physical forcing/Lower trophic levels: Coupling of physical variation ("forcing") to biological production. Here are three major scientific problems, in order of priority.

Priority I. Document changes in standing stocks using modern technology, e.g., long term moorings with acoustic instruments for determining zooplankton stock variation. What drives the interannual variation? To answer this question, the moorings should include measurements of temperature, salinity, incoming radiation, fluorescence. It is necessary to learn about interannual variation as a first step to understanding effects of regime shifts. East-west comparisons (eastern subarctic vs western subarctic gyre) should be made.

Priority II. What observations are needed to distinguish the effects of iron, Ekman pumping, cloud variation, etc. on primary production biomass? Two approaches seem feasible: (a) An Ironex experiment utilizing pairs of bio-optical drifters, one drifter receiving iron additions, the other not. Both drifters would have fluorometers and spectral radiometers to estimate changes in standing stock or production rates. (b) A process study of microherbivore control of phytoplankton stocks, with shipboard perturbation experiments to examine the feeding responses of microherbivores. The experiments would involve both dilution and enrichment.

Priority III. The Chelton–Davis hypothesis on the split of the west wind drift as it nears North America should be studied by deploying multiple drifters and with radar altimetry (TOPEX

Satellite). The hypothesis predicts that the intensity of the flow of the Alaska and California currents is out of phase and that zooplankton biomass in the California Current is high when much of the west wind drift turns south and vice versa. Chelton et al. (1982) and McGowan (1989) found zooplankton volume at central and southern California was correlated with transport in the same region. This suggests that changes in the West Wind Drift may affect zooplankton biomass in the California Current System. This should be tested and compared to transport and zooplankton biomass in the Gulf of Alaska.

Higher Trophic Levels

What are the mechanisms responsible for the sustained high biomass levels of higher trophic levels since the 1976-77 regime shift?
What are the historic biomass levels?
What is the coherence between eastern and western gyres and the Alaska Current system?
What are the linkages between the physical and biological processes?
What are the factors that regulate carrying capacity of salmon in coastal and offshore waters?

Ecosystem Interactions

What are the relative effects of exogenous and endogenous processes (including transport) that affect eastern and western subarctic productivity? For example:

1) What is the effect of the Kuroshio/Oyashio current system on the coastal ecosystems of Asia and of the deflection of these currents into the eastern Subarctic Pacific (e.g., pulses in sardine/salmon populations)?
2) What is the effect of the Subarctic Current and ENSO events on the subarctic coastal ecosystem (e.g., changes in juvenile salmon survival; changes in the hake-herring-mackerel ecosystem)?
3) What is the effect of the transition zone on the subarctic ecosystem (e.g., seasonal migrants)?
4) What is the effect of deep water community ecosystems on near surface ecosystems (e.g., changes in myctophid biomass)?

Central Questions and Research Approaches in Oceanic Subarctic

Physical Forcing – What are the characteristics of climate variability, can interdecadal patterns be identified, how and when do they arise?

Retrospection – Examine history of upper ocean thermal structure, position and width of transition zone, MLD and ENSO.

Models – Basin models, MLD, Ekman pumping, ENSO, Kuroshio/Oyashio.

Process studies – Circulation studies with idealized and real forcing functions.

Observing Systems – Moorings (T, S, MLD, acoustics, chlorophyll); Volunteer Observing Ships (T, S, fluorescence); Oshoro Maru (CTD, ADCP); drifters (CTD, fluorescence, acoustics); R/V; satellites (chlorophyll, currents, cloud cover); AXCTD (aircraft – dropped), and Autonomous Underwater Vehicles (AUV).

Note: the technology is available to instrument the region. Despite the high cost, it should be done, along with a strengthened VOS program.

Lower Trophic Level Response – How do primary and secondary producers respond in productivity, and in species and size composition, to climate variability in different ecosystems of the Subarctic Pacific? Do these changes differ from regime to regime? Why is there no spring bloom? Has phytoplankton, and zooplankton production changed with the regime shift? How do the lower trophic levels respond to perturbations in, for example, iron, or microzooplankton?

Retrospection – Examine history of nutrient data, chlorophyll, zooplankton species composition, secchi disk; MLD and light (cloud cover) as related to timing of bloom.

Models – Model zooplankton production (up to euphausiids), seasonal migration (copepods), diel migration experiments; nitrogen flux, size spectrum of phytoplankton.

Process Studies – Feeding behavior of microzooplankton, macrozooplankton feeding selectivity, field and on–board experiment with iron introduction in Gulf of Alaska (ironex) (late summer?) This study can expand on work already conducted through the SUPER program. Biological coefficients of uptake; role of gelatinous zooplankton.

Observation Systems – In addition to items under forcing (q.v.), SAR, rainfall (related to iron supply?) zooplankton abundance, species composition.

Higher Trophic Level Response – How do regime changes affect the life history patterns (distribution, vital rates and population dynamics) of higher trophic level species, through competition, and through direct response to changes in the physical environment?

Note: Effects of regime shifts may include changes in life history and behavior, migrations and distributions, growth, survival, species composition, food habits, carrying capacity, growth and size–at–age, survival, diet shifts, predation rates, reproduction success of marine mammals and sea birds (see report of subgroup 3 on carrying capacity).

Retrospection – Salmon size at maturity, scales (size–at–age), (studies underway in U.S., Japan, Canada, and Russia), life history summaries with species composition, northern fur seals (same information as for salmon), whale and sea bird feeding, distribution (see OCSEAP data), ^{15}N in fur seals and whales, and fish scales.

Models – University of British Columbia simulated currents, temperature, salmon (sockeye) migrations, bioenergetics, growth; fur seal pup survival vs temperature.

Process Studies – Salmon growth vs age–at–maturity (Auke Bay), diel feeding studies, thermal limits (large scale), small scale distribution.

Observation Systems – Japan, Canada, and USA studies of winter distribution of large nekton squids, gillnet comparisons (Oshoro Maru), food habits (diet shifts), vertical distribution (salmon) – acoustic tags. Non–commercial forage fishes (myctophids, smelts, atka mackerel), stock distribution of salmon (hatchery, wild), distributions and migrations of nekton and marine mammals, age and growth of nekton, changes in species composition and abundance, foraging behavior, reproductive success of sea birds and mammals.

Ecosystem Interactions – How are Subarctic Pacific ecosystems structured? Do higher trophic levels respond to climate variability solely as a consequence of bottom up forcing? Are there significant intra–trophic level and top down effects on lower trophic level production and on energy transfer efficiencies?

Note: Issues include the microbial loop, competition, predation rates (including human predation), food–web structure and efficiency, and particle fluxes. Of particular importance are comparisons between events and processes in the Alaska Current and those in the Subarctic Gyre, and between the east and west gyres.

Retrospection – Change in species composition and shifts in species dominance before and after regime changes, $N0_3$ in scales, teeth, baleen.

Model – model salmon trophodynamics, linkage with lower and higher trophic levels, size spectrum theory, production/biomass (P/B) ratios, marine mammal food web, Sverdrup theory on initiation of spring bloom, re–visit Laevastu model, European Regions Seas model (ERSEM).

Process Studies – Establish biological coefficients for models, coastal studies on juvenile salmon predation, sediment trap– ^{15}N, role of seasonal migrants, isotope studies (Cs–K) of trophic levels.

Monitoring – add sediment traps.

BERING SEA BREAKOUT SESSION

Discussion Leaders: Alan Springer and James Overland
Participants: Vera Alexander, Hal Batchelder, Paul Bentzen, Ned Cokelet, Dan Costa, Tina Willie Echeveriia, Robert Francis, George Hunt, Evelyn Lessard, Patricia Livingston, Richard Merrick, Kate Myers, Jeff Napp, Thomas Powell, James Schumacher, Gary Sharp, Phyllis Stabeno, Gordon Swartzman, Vidar Wespestad, Anne York

Introduction

The Bering Sea shelf is possibly the most productive of the northern high latitude seas. The foundation is a greenbelt of primary productivity in excess of 200 gC m^{-2} yr^{-1} extending over the outer 200 km of the shelf. This region supports some of the worlds largest stocks of fish. For example the biomass of the walleye pollock stock is estimated to be approximately 10 million metric tons. Likewise, the largest runs of salmon in the U.S. is the Bristol Bay sockeye run. The region has historically supported large populations of marine mammals and seabirds. The benthos of the Bering Shelf is also productive, supporting large populations of King crab, flatfish and a variety of infauna.

The Bering Sea is an appropriate region in which to study the potential effects of climate change on carrying capacity. There is a rich background of long term monitoring studies of northern fur seal and marine birds at the Pribilof Islands; fisheries catches for numerous species in the eastern Bering Sea; and process studies of the determinants of production and the linkage of production to interannual variation in weather patterns (PROBES and ISHTAR). These studies provide a basis for developing additional process oriented studies for extrapolating the effects of short term changes in weather to longer term climate changes.

The SE Bering Sea has the following characteristics:

- The boundary of the arctic and maritime air masses occurs here; small climate shifts might provide major differences in wind intensity, ice extent and cloudiness.

- It has a broad, shallow shelf. Tidal and wind mixing create three domains based on stratification with strong frontal boundaries between domains.

- There is weak or no advection on the shelf. However, there is interaction of shelf waters with the deep basin of the Bering Sea and perhaps also with the Gulf of Alaska through the Aleutian Chain.

- Primary and secondary production is tied to mixed layer dynamics, which are primarily controlled by storm frequency and the extent and timing of ice cover.

- Upper trophic level productivity is high, and top down controls have a strong influence on the species mix of the system. Of particular interest is the cannibalistic character of walleye pollock.

• Timing of spring bloom relative to storm tracks determine whether energy input is to the benthic or pelagic communities. If the spring bloom occurs when the ice is present, the primary production sinks out of the pelagic zone due to inhibition of grazing at low temperatures (Cooney and Coyle, 1982).

Breakout Discussions

First order understanding of the Bering Sea has been obtained by previous repeated surveys and process oriented studies (e.g., PROBES, Bering Sea FOCI). What is needed now is to quantify the causality between the magnitude of environmental change and the response of the system. The natural variability of the system is large so that it may be possible to find historical analogs of climate change. The primary question is how does climate variability modulate the high productivity of the Bering Sea? Specifically, storm tracks and extent of seasonal ice edge are known to vary on a 7-15 yr cycle, will a climate shift in storm tracks alter the distribution of energy between the pelagic and benthic components of the SE Bering Sea shelf ecosystem? The following research issues have been noted qualitatively. What is required is quantified answers to the following questions.

• What is the pelagic biogeography of the Bering Sea?

• Where in the Bering Sea do significant processes occur?

• What is the importance of production over the shelf, shelf edge, and basin of the Bering Sea to biomass yield at higher trophic levels?

• Are all habitats equally susceptible to climate change?

• Is the magnitude of variability proportional to habitat importance? i.e.., primary or secondary productivity of a given habitat might vary dramatically in response to climate change but it might be irrelevant to most higher trophic levels.

• What is the relation of the range of storm activity to the annual production budget and food web dynamics in the mixed layer?

• What is the contribution of the sea ice melt–back bloom to total annual production?

• How does the nature (e.g. timing and magnitude) of the spring bloom affect total primary production and the partition of energy between pelagic and benthic ecosystem components? Specifically, does an early bloom lead to high benthic production and a late bloom lead to high pelagic production?

• Will climate change alter habitat/domain volumes and how will this influence recruitment?

• What are the similarities and differences between the Bering Sea and Southern Ocean shelf sea-ice and pelagic sea-ice communities?

Activities

We recommend activities in the areas of retrospective, modeling, process studies and monitoring. An initial approach should be to identify key species in the production and transfer of energy in the ecosystem, identify species sensitive to change in production at lower trophic levels, and develop studies around those species.

Retrospective Studies

- Examine sediment cores from anoxic basins for evidence of decadal and secular fluctuations in the abundance of marine fishes.
- Determine the summer distributions of marine fish relative to environmental variables such as fronts, ice cover during the previous winter, lagged wind and water temperature.
- Examine growth rates of marine fish relative to environmental variables and summer distributions.
- Examine marine mammal growth patterns and isotope ratios to estimate level of trophic feeding coupled with variations in food availability.

Modeling / Ecosystem Interaction Studies

- Construct a physical model for the shelf and basin incorporating historical records of storm tracks and intensity to predict the interannual range of nutrient dynamics and primary production.
- Construct a multispecies virtual population analysis (MSVPA) of the eastern Bering Sea including commercially important fish, and other predators such as mammals and birds to determine if stable predator selectivity estimates are obtained.
- Construct a spatially explicit trophodynamic model of the eastern Bering Sea that includes upper trophic level predators, primary and secondary production, and linkages to physical processes.

Process Oriented Studies

- Determine food chain lengths and trophic relationships using isotope, pigment, and dietary approaches.
- Determine the role of jellyfish, other carnivorous zooplankton, squid, and myctophids in the pelagic food web.
- Determine predator selectivity and switching parameters (particularly adult pollock as predator) by sampling predators in prey patches containing different proportions of zooplankton and juvenile pollock. Quantitatively assess zooplankton (including euphausiids) and juvenile pollock in these patches.
- Determine the contribution of sub–stocks to pollock recruitment by assessing the location and density of spawning sub–stocks and tracking the fate (location and survival) of spawning products of each sub–stock and determine how climate affects variability in both spawning locations and fate of spawning products.

Monitoring/ Lower Trophic Level Response

- Determine seasonal and interannual variability in floristics, primary production, and carbon sedimentation rates at key index sites in shelf and basin domains of the eastern Bering Sea.
- Determine seasonal and interannual variability in abundance and production of key species of herbivorous and carnivorous zooplankton in the shelf and basin domains of the eastern Bering Sea.
- Determine interannual variability in infaunal benthos abundance and location at key index sites in the inner, middle, and outer shelf regimes of the eastern Bering Sea.

Monitoring / Higher Trophic Level Response

- Determine interannual and seasonal variability in juvenile pollock abundance, location, vertical distribution and diet throughout the eastern Bering Sea, especially in relation to ice dynamics.
- Determine interannual variability in other forage fish abundance, location, and diet.
- Conduct predator food habits and energetics survey to determine seasonal variation in juvenile pollock, other forage fish, squid and zooplankton utilization by higher trophic level predators.
- Determine interannual variability in the abundance and spatial distribution of spawning pollock.
- Conduct summer near–shore midwater surveys of the Bering Sea coast to determine abundance and location of capelin and herring.
- Conduct seasonal surveys of forage fish abundance and location relative to upper trophic level predators.
- Determine the role of gelatinous zooplankton in mediating the effects of climate change through competition for food with high trophic level species.
- Measure foraging effort, behavior and energetics of key species of mammal and birds as index of change in predator effort. Examine differences in onshore versus offshore foraging effort in fur seals.
- Compare eastern and western Bering Sea ecosystems. The Eastern Bering Sea is a shelf based system, productivity coupled with extent of sea-ice edge. It is a low advection region. The Western Bering Sea is a high advection system, deep water environment. Both regions have many of the same species and would provide an interesting comparison as to where and how these species make a living in such different oceanographic regions.

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APPENDIX 1—CLIMATE CONTEXT

The hypothesized changes for the Gulf of Alaska and Sub-Arctic Pacific, and for the Bering Sea, expected to accompany greenhouse gas-induced climate change are summarized in Tables 1 and 2, respectively (pp. 28-29). The object of these tables, and their attendant discussions, is to summarize the results of thought experiments using the relatively crude projections now being made by the climate community. A special attempt was made to be at least internally consistent with the speculations itemized below. It is important to note that these speculations are based on the assumption of a secular warming of the atmosphere over the North Pacific, especially at higher latitudes. The present climate is punctuated by decadal-scale variations or regime shifts of substantial amplitude, as is discussed in the following section. It is highly likely that these types of variations will continue, and at any particular time, their effects can swamp the changes associated with global warming.

Gulf of Alaska and Subarctic Climate Change Scenario

With global climate change (for this scenario, a warming), it is predicted that the rate of temperature change at high latitudes will be greater than at lower latitudes. This would serve to decrease the meridional thermal gradient that would result in a more sluggish atmospheric circulation. This is the primary assumption that will be used to describe the subsequent affects on the marine ecosystem.

With a decrease in the atmospheric meridional thermal gradient, storm intensity would decrease and the storm tracks would be shifted northward (Table 1). The zero wind stress curl line that separates the subarctic and subtropical gyres would shift poleward, as would the bifurcation of the Alaska and California Currents. Previous results have suggested that a northward shift of westwind drift could result in an intensification of the currents of the Alaska gyre. A reduction in the wind stress curl would result in a decrease in transport, but the split between the southward flowing California Current and northward flowing Alaska Current is unknown. Any change in northward transport will effect the poleward heat flux.

Decreased storm activity over the GOA is likely, especially in winter. The ramifications for the central Gulf are less upwelling and less wind mixing. In terms of surface heat fluxes, there will likely be decreases in sensible heat flux, but unknown changes in evaporation. The net effect will be a shallower mixed layer depth and warmer mixed layer temperatures.

An increase in absolute humidity in the atmosphere would likely result in increased coastal precipitation. At present maximum freshwater runoff occurs in the fall, since the high precipitation rates of winter are tied up in snow. As air temperatures warm, more of the winter precipitation would fall as rain. The warmer temperature could decrease the size of the coastal glaciers, thus increasing runoff at least in the near future. Maximum runoff would likely occur in winter coinciding with the maximum wind stress. The increase in freshwater runoff and warming would increase the stratification along the coast. The decrease in upwelling and warming in the central North Pacific would have competing effects on stratification, but the increases in temperature would probably dominate.

Decreased wind stress along the coast would result in a weaker Alaska Coastal Current (ACC). The increase in freshwater would add to the baroclinic structure, but the reduction in wind stress would weaken the confinement along the coast and thus decrease the baroclinic gradient. Thus any change in the number and intensity of eddies formed on the shelf is unknown. The effect of climate change on the eddies at the shelf break is also unknown.

Diminished downwelling on the shelf would tend to reduce the cross-shelf flux of nutrient-poor water at upper levels, but this mechanism would be counteracted by less wind mixing, with an unknown net effect on nutrient concentrations over the shelf. The reduction in the strength of the ACC would effect the transport of nutrients on the shelf. The timing of the spring bloom would probably be earlier since the water would be warmer, and the formation of the spring mixed layer could be earlier.

Bering Sea Climate Change Scenario

I. Atmosphere

Surface air temperatures (Increase)—There is a strong consensus among the climate community that global warming will be accompanied by enhanced surface temperature rise at higher latitudes, largely due to positive feedback effects associated with less snow cover and sea ice and hence lower albedo (Table 2). The Bering Sea region is at a high enough latitude that it is expected to warm significantly.

Storm intensities (Decrease); Storm frequencies (Increase)—The enhanced warming at high latitudes will have the effect of reducing the meridional gradient in air temperature at mid-latitudes; this reduction in baroclinity will lead to weaker storms (Table 2). The zone of maximum baroclinity will tend to shift poleward. Since the storms now track across the North Pacific in a mean sense south of the Bering Sea (Anderson and Gyakum 1989), a northward shift of this track will tend to cause a higher incidence of storms in the Bering Sea (as suggested by the GCM simulations of Hall et al. 1994).

Sea level pressure (Decrease in N. Bering); Southerly wind (Increase); Wind stress curl (Unknown, competing effects)—Sea level pressure is expected to be significantly lower in the Arctic, as suggested by GCM simulations and from hydrostatic considerations assuming relatively strong warming in the Arctic (Table 2). This effect will tend to cause lower sea level pressure in the northern portion of the Bering Sea, and more winds from the south, especially in the vicinity of Bering Strait. It is unknown how the mean wind stress curl is likely to change, since it is net effect of the storms that largely determines the curl, and there is likely to be compensation between changes in the frequency and intensity of the storms. It is probable that the location of the maximum in the curl will shift poleward from its present position along the Aleutians (e.g., Bond et al. 1994).

Humidity, Precipitation, Fresh water runoff (Increase)—Warmer air temperatures allow higher water vapor concentrations and would be expected to lead to greater precipitation amounts, as also indicated by GCM results (Table 2). Greater fresh water runoff is then also expected. These effects are liable to be more pronounced in the northern Bering Sea.

II. Circulation and Transports

Alaskan Stream (Probable decrease)—The Alaskan Stream (AS) is expected to decrease in intensity because enhanced rises in sea level (Gregory 1993) and reduced wind stress curl is expected in the central North Pacific. These effect may be tempered by greater storminess in the Gulf of Alaska (See Table 1).

Near Strait Inflow (Decrease)—This primary source of inflow into the Bering Sea is expected to decrease due to a decrease in the intensity and the westward extent of the AS, and perhaps also due to changes in Sverdrup transports associated with a weakening and northward displacement of the wind stress curl.

Bering Slope Current (Decrease)—This flow is expected to decrease because a reduced AS will supply less mass transport through the Aleutian passes, and because of reduced baroclinity between the deep basin and shelf water masses. As with the Near Strait inflow, it should also tend to weaken due to reduced deep Bering basin Sverdrup transport.

Kamchatka Current (Decrease)—The Kamchatka current will decrease if the Near Strait inflow is less and the Sverdrup forcing is reduced, as suggested above.

Bering Strait Outflow (Unknown, competing effects)—The meridional component of the wind, which is expected to be more from the south, would tend to cause more outflow. This effect is liable to be counteracted by a decrease in the steric difference between the Bering Sea and Arctic Ocean.

Unimak Pass inflow (Unknown)—The portion of the Alaska Coastal Current (ACC) that remains on the shelf flows through Unimak Pass. The ACC is largely due to the set-up associated with the along-shore winds. A change in the storminess of the Gulf of Alaska would result in a change in the total transport by the ACC, but there may also be changes in the fraction of the ACC that stays on the shelf to flow through Unimak Pass.

Shelf coastal current (Unknown)—This current originates from the inflow through Unimak Pass and therefore its change is uncertain. It may tend to be enhanced by greater freshwater runoff from the west coast of Alaska.

III. Hydrography

Sea level (Increase)—A significant rise in sea level is expected due to the steric effect and melting of glaciers and ice packs.

Sea surface temperature (Increase)—The SST is expected to warm substantially due to warmer air temperatures and greater downwelling longwave radiation from a more humid atmosphere. There may be a positive feedback associated with warmer SST's promoting the breakup of stratus cloud decks in summer months and hence greater solar insolation.

Shelf bottom temperature (Increase)—The cold water that is presently found near the bottom on the shelf is formed by convective cooling due to melting of ice advected from the north. With less ice created and advected in the northern portion of the Bering Sea, this mechanism will be suppressed.

Basin stratification (Increase)—The ocean warming should be enhanced near the surface, promoting the static stability.

Shelf stratification (Unknown, competing effects)—The change in static stability over the shelf is unknown because both the near surface and bottom waters are expected to warm.

Mixing energy (Decrease)—Much of the mixing is accomplished by storms, which are expected to be more frequent but weaker. Since the strongest storms cause a disproportionate share of the mixing (mixing rate varies roughly with the wind speed cubed), a net reduction is expected in the wind energy available for mixing. At least over the deep Bering basin, vertical mixing is also liable to be suppressed by increased upper-level static stability. An important aspect of mixing is its seasonality, especially as it applies to nutrient supply and primary productivity, but changes in this seasonality are uncertain.

Eddy activity (Unknown)—The mechanism(s) responsible for eddy generation in the Bering Sea are not well understood, especially in its eastern portion where the mean currents are weak and the eddy activity is high. The flow along the eastern slope and shelf break is expected to decrease as noted above, but it is not evident how this change would impact the eddies. Increased river flows may generate and sustain eddies in areas of the Gulf of Alaska and the Bering Sea. This should have the effect of entraining nutrients and increasing local productivity.

Shelfbreak nutrient supply (Decrease)—This is expected to decrease because of reductions in the slope currents and perhaps the wind-driven upwelling along the shelfbreak during the summer. These effects will tend to be augmented by an increased supply of low nutrient water from estuaries.

IV. Sea Ice

Extent, Thickness, Brine rejection (Decrease)—The ice in the Bering Sea is generally confined to shelf regions. It is generally formed in coastal regions and the southward march of its leading edge is mostly due to advection. Its extent over the shelf is expected to be substantially reduced for two reasons: warmer air temperatures and less wind from the north, especially in winter. A shorter freezing season will tend to produce thinner ice. Less ice formation implies a decrease in brine rejection.

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