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

North Pacific Climate Change and Carrying Capacity (CCCC) Science Plan

U.S. Global Ocean Ecosystems Dynamics

Report Number 16

December 1996

U.S. GLOBEC

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This is a report of a U.S. GLOBEC Workshop on North Pacific Climate Change and Carrying Capacity held in Seattle, WA, USA, at the Battelle Conference Center from 31 January - 2 February 1996. Hal Batchelder and Anne Hollowed acted as rapporteurs and summarized the discussions that occurred in the Subarctic Pacific and Bering Sea working groups, respectively. Anne Hollowed chaired the meeting and compiled and edited this report.

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PREFACE

Planning for a U.S. GLOBal ocean ECosystems dynamics (U.S. GLOBEC) - related program in the North Pacific was initiated with a workshop sponsored by U.S. GLOBEC held in Seattle, Washington, April 19-21, 1995. That workshop brought together over 75 scientists; a summary of the workshop was published as U.S. GLOBEC Report 15 (U.S. GLOBEC 1996). The need for the workshop reported on in this document stemmed from the development, in October 1994, of a Science Plan for coordinated research on Climate Change and the Carrying Capacity (CCCC) by the North Pacific Marine Science Organization (PICES). Copies of the Science Plan and Implementation Plan for the PICES-GLOBEC CCCC Program are available from the PICES Secretariat, IOS, Sidney, B.C., Canada. The U.S. GLOBEC CCCC program will address how climate variability affects ecosystem structure and the productivity of key biological species at all trophic levels in the open subarctic and coastal North Pacific. The program is designed to be a U.S. contribution to a larger international research effort involving the six member nations of PICES (Canada, China, Korea, Japan, Russia, and United States) and GLOBEC International.

EXECUTIVE SUMMARY

This report summarizes discussions of a workshop held at the Battelle Conference Center in Seattle, Washington on 31 January–2 February 1996 in anticipation of potential future funding for a U.S. GLOBEC program in the North Pacific. Twenty-three oceanographers or fishery scientists attended the workshop. After initial plenary sessions the participants divided into two groups: one to discuss the Bering Sea and one focusing on the Subarctic Pacific. Each group developed hypotheses that could become the basis for U.S. GLOBEC science in those regions. The hypotheses, target species and recommended approaches for research in the Subarctic Pacific and Bering Sea regions of the North Pacific are detailed in the report.

Subarctic Pacific Program

Hypotheses

- Ocean survival of Pacific salmon is determined primarily by survival of juvenile salmon in coastal regions, and is affected by interannual and interdecadal changes in Gulf of Alaska physical forcing.

- Variation in size-at-age of returning salmon is determined largely by interdecadal and interannual variation in physical conditions and productivity of the oceanic realm of the subarctic Pacific, and may show density dependence.

Target Species

- Salmon (esp. pink salmon, *Oncorhynchus gorbuscha*)
- Prey of salmon, but especially large calanoid copepods and euphausiids
- Predators of salmon (pollock; herring; marine mammals; birds)

Approaches

The group elected to focus the Subarctic Pacific Program on the first of the two hypotheses listed above, because that aspect—focusing on factors influencing survival of the juveniles during the nearshore phase of their ocean life history—appeared amenable to a U.S. GLOBEC regional study. Following the general U.S. GLOBEC strategy, the group recommended monitoring, process-studies, modeling and retrospective analysis. A potential study region on the continental shelf outside of Prince William Sound in the Northern Gulf of Alaska was identified as a potential site for U.S. GLOBEC studies because it complements and will benefit from 1) ongoing investigations by the Exxon Valdez Oil Spill Trustees Sound Ecosystem Assessment (SEA) program in Prince William Sound, and 2) planned (or ongoing) shelf-wide surveys of the distribution of juvenile salmonids by the Ocean Carrying Capacity (OCC) program of the Auke Bay Laboratory of the National Marine Fisheries Service (NMFS). Large-scale monitoring of the region should be accomplished through a combination of remote sensing and a few strategically placed moorings, drifters, ship-visited transects, and modeling. Intensive process studies should be conducted for several years in one or more of the regions surrounding the repeat transects and moorings comprising the monitoring system. The focus of the process studies would be to examine the biological and physical processes that determine growth and survival of juvenile salmon in the coastal zone. This would require observations of a) the physical environment, b) secondary production processes, c) diet of juvenile salmon and their competitors and predators, d) the distribution and abundance of salmon predators, and e) growth rates of juvenile salmon. Recommendations for specific retrospective and modeling studies were also made, but the group focused on the monitoring and process-oriented aspects of a subarctic Pacific U.S. GLOBEC study.

Bering Sea Program

Hypotheses

- Zooplankton production in the Bering Sea is primarily directly or indirectly controlled by four physical processes: a) advection, b) stratification, c) sea ice coverage, and d) water temperature (the extent of the cold pool).

- Annual zooplankton production is primarily controlled by predation and interannual variability is controlled by the distribution and abundance of higher trophic level predators.

- Zooplankton production is jointly controlled by the physical processes and the predator-related processes as described in the above two hypotheses.

Target Species

- Zooplankton (copepods; euphausiids)
- Seabirds (Least Auklet)
- Pelagic Fish Stocks (pollock; herring; sockeye, pink and chum salmon)
- Forage Fish Species (capelin; sand lance; myctophids; bathylagids)
- Other Invertebrates ("jellyfish"; cephalopods; chaetognaths)
- Other large predators (northern fur seals; kittiwakes; murres; piscivorous flatfish; Pacific cod)

Approaches

This working group also discussed monitoring, modeling, retrospective analysis and process-oriented studies. In addition, they also discussed technology related issues. In the arena of retrospective analysis, a key problem is to establish the pattern of natural variation in physical forcing and ecosystem response. Biological data sets available to examine this include walleye pollock and sockeye salmon population abundances, and salmon migration pathways. Physical data include information on ice extent, some temperature data, and several atmospheric variables. A suite of types of physical, biological and coupled biophysical models in the Bering Sea were discussed and should be supported. Monitoring efforts should focus on acquiring observations of the physical, chemical and biological environment to examine interannual variability over an extended period. Several regions were identified as valuable sites for monitoring of physical (e.g., transport through Amukta Pass; ice-edge position, melting cycles because of its influence on productivity; transport processes in the Unimak Pass, an indication of Alaskan Coastal Current strength) and biological (Pribilof Island region, because of the extensive ecosystem work, especially on higher trophic level organisms) processes. Process-oriented studies should focus on the key species and the factors which control their production. Thus, they should be conducted at the appropriate space and time scales to examine zooplankton and fish production in relation to physical features (fronts, eddies, position of the ice edge, extent of the cold pool) that may vary both seasonally and from year-to-year. Advancements in optical, acoustical and biomolecular technology that permit more resolution (or comprehensive) sampling should be employed in a U.S. GLOBEC Bering Sea program.

INTRODUCTION

The U.S. GLOBEC program was developed to improve our understanding of the influence of physical processes on marine ecosystem dynamics in order to predict the response of the ecosystem and the stability of its food web to climate variability. U.S. GLOBEC advocates a multi-disciplinary approach including combinations of field studies, model and technology development, and retrospective studies (U.S. GLOBEC 1995). U.S. GLOBEC has identified several ecosystem types for emphasis in its research program. This report contains a science plan for U.S. GLOBEC-sponsored research in the subarctic Pacific and Bering Sea.

The ecosystems of the subarctic Pacific and Bering Sea are ideal candidates for a U.S. GLOBEC research program. The region supports some of the world's largest populations of commercially important fish and shellfish resources. These abundant resources appear to be sensitive to the geographical distribution of the changes in the atmosphere-ocean climate system. Both short-term (seasonal) and long-term (decadal) climate variations appear to significantly impact the biological environment (see collection of papers in Beamish, 1995; Beamish and McFarlane, 1989, U.S. GLOBEC 1996)

These strong biological responses to climatic variability translate into direct impacts on the efficiency and sustainability of the region's valuable fishing industry. Approximately one half of the total U.S. fisheries catch is removed from waters off the coast of Alaska (NMFS 1993). Elucidation of 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.

Initiating a U.S. GLOBEC research program in the subarctic Pacific and Bering Sea is timely because of the coincidental development of an international research program on Climate Change and the Carrying Capacity (CCCC) of the North Pacific sponsored by the North Pacific Marine Science Organization (PICES) and GLOBEC International. The PICES-GLOBEC CCCC program is a cooperative research program sponsored by the national research programs of the six member nations of PICES (Canada, China, Japan, Korea, Russia, and the United States). A U.S. GLOBEC program in the North Pacific would utilize newly developed research tools and technologies to study questions of climate change and carrying capacity of the subarctic Pacific and Bering Sea. These include measurement technologies and complex computer models which make a large scale research program like the one proposed here, a realistic endeavor.

Both U.S. GLOBEC and PICES-GLOBEC recommend research at the basin and regional scale. Regional scale studies will occur in the coastal waters of each member nation of PICES. The next steps in developing the CCCC implementation plan on the regional scale are expected to include efforts to design comparisons of ecosystem properties and responses to climate variability. Basin- scale research will require the development of an international cooperative program. This Science Plan details potential research activities of a U.S. GLOBEC program in the subarctic Pacific and the Bering Sea.

Physical Oceanographic Setting

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. 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.

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 conditions in the Bering Sea are also influenced by the extent of ice cover (Fig. 2). 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 and stratification.

Evidence of decadal-scale variability in climate conditions and regime shifts is prevalent in the North Pacific and Bering Sea. The climate of the Subarctic Pacific changed during the late 1970s. The Aleutian Low intensified (Trenberth and Hurrell, 1994) and coastal sea surface temperatures rose rapidly by several degrees (Rogers and Ruggerone, 1993; Royer, 1989; Graham, 1995). The most recent shift occurred in the late 1970s.

Study Regions

The PICES 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 to compare how variations in ocean climate affect species dominance and fish populations at the coastal margins of the Pacific Rim.

U.S. GLOBEC-sponsored activities should occur in the coastal regions of the Gulf of Alaska, the eastern Bering Sea and the open subarctic ocean. The geographic boundary between the coastal regions of the Gulf of Alaska and the open subarctic has not been defined by PICES. The following working definition is offered by U.S. 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.

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. This coastal region will include areas south of the Aleutian Islands.

Some species, such as Pacific salmon, undertake seasonal migrations that cross both the

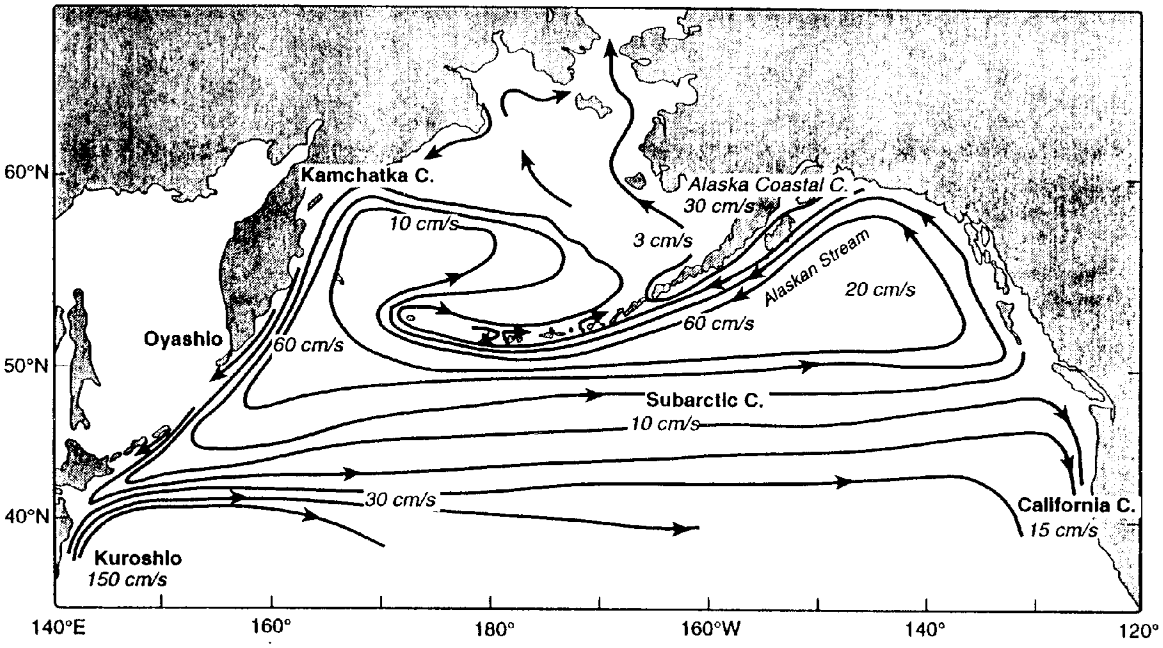

Figure 1. Estimates of climatological mean surface circulation in the subarctic Pacific after Reed and Schumacher, 1985.

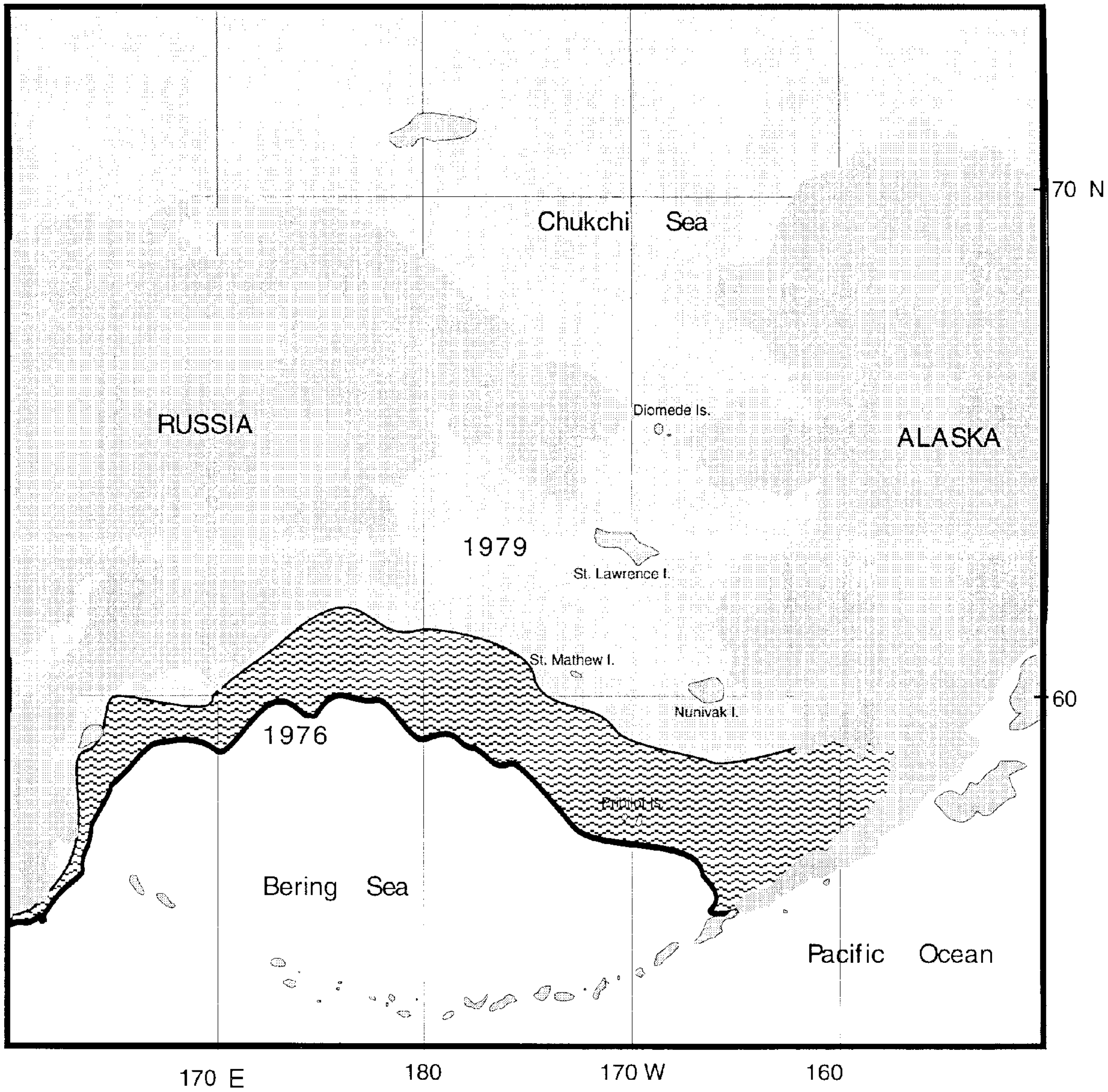

Figure 2. Sea ice extent over the Bering Sea in an heavy ice year(1976) and a light ice year (1979). (from Wyllie-Echeverria, 1995)

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.

Central Scientific Issues

The PICES Implementation Plan presented a set of Central Scientific Issues. Key research activities related to these issues will include retrospective analyses, development of models, process studies, development of observational systems, and data management. 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?

Examples of potential U.S. projects that could be conducted to address the subset of questions for each of three study regions (the oceanic and coastal domains of the Subarctic Pacific and the Bering Sea) were advanced at the U.S. GLOBEC sponsored workshop held in 1995 (U.S. GLOBEC Rept. No. 15, 1996).

Coordination with On-going Programs

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 CCCC 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 1994b). Coordination with the California Current program is highly desirable because large-scale forcing for both regions could be modeled simultaneously.

The North Pacific is a desirable region for U.S. GLOBEC research efforts partially because of the potential for coordination with seven 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 (PMEL), the Alaska Fisheries Science Center (AFSC), 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 National Oceanic and Atmospheric Administration's (NOAA) Coastal Ocean Program (COP), 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: a) investigation of stock structure of pollock in the Bering Sea; and, b) 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 COP. The SEBSCC study 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 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.

5. NMFS Ocean Carrying Capacity Studies (OCC). The AFSC's 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.

6. 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.

7. Biophysical Controls of Salmon Migration and Production (BCSMP). BCSMP is a three-year research program at the University of British Columbia, Canada which is funded by Natural Sciences and Engineering Research Council (NSERC). The program is focused on large scale ocean currents and their influence on Pacific salmon migration and production. Funding for this program terminates in 1996.

RESEARCH PLANS

Subarctic Pacific Program

Working Group Members: Jack Barth, Hal Batchelder, Ted Cooney, Dan Costa, Ken Denman, Bruce Frost, Steve Hare, Jack Helle, Art Kendall, William Pearcy, Bill Peterson, Tom Royer, Ted Strub, and Warren Wooster

Program Rationale

Early in the meeting, it was decided that the two working groups on the Oceanic Subarctic and the Coastal Gulf of Alaska should meet as a joint working group. It was felt that the division of the Pacific into a coastal and oceanic realm was artificial, and that one of the questions that U.S. GLOBEC might want to address is the exchange of water and organisms between the two environments. Consequently, below we describe a program of research for U.S. GLOBEC that considers both the oceanic and coastal regions.

Based on several of the presentations made at the workshop, and the early discussions of this working group, we formulated two hypotheses on which a subarctic Pacific U.S. GLOBEC effort could be based. They are as follows:

> **Hypothesis 1 (H1): Ocean survival of Pacific salmon is determined primarily by survival of juvenile salmon in coastal regions, and is affected by interannual and interdecadal changes in Gulf of Alaska physical forcing.**
>
> **Hypothesis 2 (H2): Variation in size-at-age of returning salmon is determined largely by interdecadal and interannual variation in physical conditions and productivity of the oceanic realm of the subarctic Pacific, and may show density dependence.**

These two hypotheses imply a first-order independence of mortality and growth processes. H1 implies that the survival of salmon populations is principally determined by coastal conditions, early in the juvenile phase. H2 suggests that final size (weight) of those individuals which survive the early juvenile phase in coastal waters is reflective of growth occurring during their final and/or penultimate year, when they are feeding in the oceanic realm of the subarctic Pacific. Density dependence of growth rate may occur if early juvenile mortality is low, a large number of salmon survive to exploit a common resource in the oceanic realm, and competition for that resource occurs. In this way, growth rates in the later phase are coupled to mortality rates in the early phase.

The working group realized that detailed, process-intensive studies of both the oceanic and coastal realms of the subarctic Pacific would not be feasible with the resources likely to be available for a U.S. GLOBEC study. Process-oriented research and surveys in a focused coastal study were designed to address H1. These are more feasible, with limited resources, than the larger-scale process studies in the deep ocean that would be needed to address H2. However, in order to connect a coastal Gulf of Alaska ecosystem study to climate forcing, we recommend that some specific limited biological and physical observations be obtained at the basin (gyre) scale. Figure 3 provides a diagram (cartoon) of the types of observations needed to make that connection; specifics of this diagram are described in the later sections on monitoring, modeling and process studies.

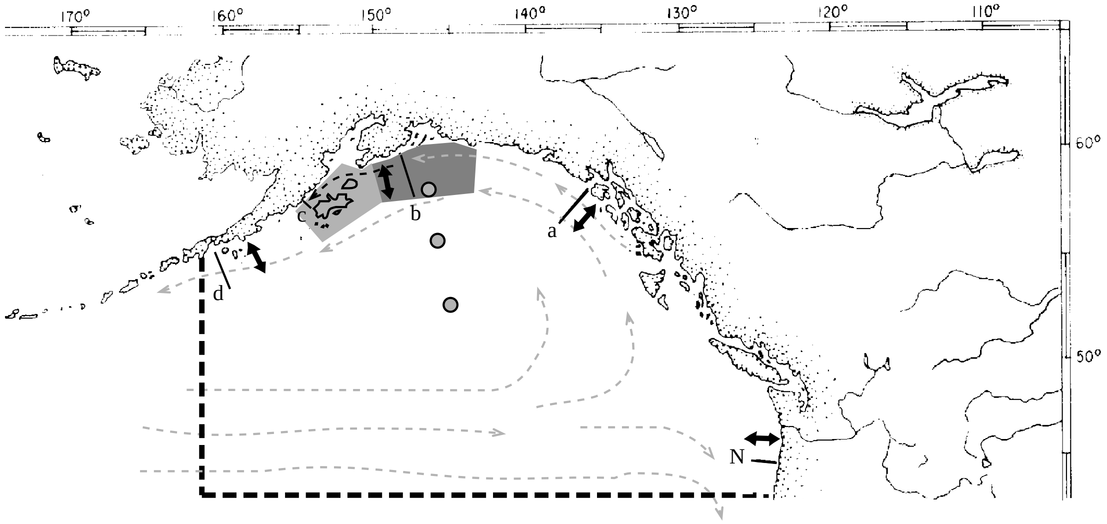

Figure 3. Diagram showing the subarctic Pacific with proposed study region in the Northern Gulf of Alaska (outside of PWS, but extending westward into the Shelikof Strait and Kodiak Island region). Shading indicates regions for studies of cross-shelf exchange (large double-headed arrows) of plankton and salmon (darkest tint) and larger region (lighter tint) for examination of salmon survival, especially predation mortality. Potential monitoring transects in the subarctic Pacific are shown as black lines (a-d). Line N is a potential monitoring site (Newport, OR) for comparison. Large circles are deep water moorings in the Gulf. Not shown are satellite observations, VOS sampling, and details of sampling in the process-study regions. The dashed line delimits the region within which PALACE floats or other Lagrangian instruments could be deployed.

Key Species

For a number of reasons, salmon quickly became the focus of the research program. First, catch of several regional salmon stocks show shifts that appear to be strongly associated with the apparent shifts in climate (as indicated by the North Pacific Index or Kodiak Winter Air Temperature) that occurred in the North Pacific in 1976-77 (Fig. 4; Francis and Hare, 1994). Moreover, detailed intervention analysis of the time series of stocks indicates that the pink salmon stocks responded to the environmental shift a year earlier than the sockeye salmon stocks. The differing time lags of the two species relative to the climate shift are (1) consistent with the different durations of the oceanic phase of their life-history (e.g., pink salmon have a two year life cycle; sockeye salmon 2-3 years), and (2) suggest that the effect of the climate change on salmon abundance occurred during the earliest marine phase of the life history (i.e., as juvenile salmon in coastal regions of the Gulf of Alaska). Moreover, the difference in the timing demonstrates the importance of examining the responses of multiple species. Without the species comparison it would have been difficult to determine the phase of the life history at which the "climate [=regime] shift" had an impact; with the multiple species we have a strong indication that it occurred during their early marine phase, when the species were distributed inshore rather than dispersed across the oceanic realm. "Pacific salmon" include five North American species (and numerous individual stocks): chinook (*Oncorhynchus tshawytscha*), sockeye (*Oncorhynchus nerka*), coho (*Oncorhynchus kisutch*), chum (*Oncorhynchus keta*) and pink (*Oncorhynchus gorbuscha*). Of these, this working group recommends that a U.S. GLOBEC process study in the North Pacific focus on chum and pink salmon, especially the latter. These two species have much shorter residence times in freshwater, thus they enter the coastal ocean environment at a smaller size, and are more likely to be susceptible to predators and food limitation than are the other salmonids (chinook, coho, sockeye). Pink salmon have a short generation time (two years), which provides a quick turnaround time from their entering the ocean to their return, which affords U.S. GLOBEC the opportunity to examine the success and dynamics of several year classes within a five to seven year time-frame study. The decision to focus process studies on chum and pink salmon is made to isolate as much as possible the conditions responsible for mortality and growth on the oceanic (as opposed to the freshwater phase) side of the life-cycle, specifically in the early juvenile phase while the population transits the coastal region enroute to the deeper, offshore region.

Second, salmon from different regions of the North Pacific have responded differently to the recent warming that has occurred in the North Pacific. Recently, salmon stocks (especially sockeye and pink salmon) of Alaska and British Columbia have been at historic high levels (Beamish and Bouillon, 1993), while more southerly stocks (mostly coho and chinook salmon) from California, Oregon and Washington are at very low levels of abundance. This dichotomy provides U.S. GLOBEC with an opportunity to conduct comparative studies that focus on salmon from both the subarctic realm of the North Pacific in the present project and from the southern region off the NW U.S. (as part of the NOAA/COP Northwest Pacific Coastal Ecosystem Regional Study Program, now in its initial year, and possibly as part of a U.S. GLOBEC California Current study).

Third, salmon are both economically and ecologically important in the North Pacific Ocean. The value of the 1992 Alaskan statewide catch (314,200 t) has been estimated at $575 million (NMFS, 1993).

Finally, there are extensive historical data on salmon abundances and opportunities to examine past vital rates (e.g., growth, size-at-age using archived scale samples) of salmonids. In accord with the U.S. GLOBEC paradigm, by selecting salmon as a key species, we are also interested in the abundances, distribution, and dynamics of their prey and predators. Thus, the

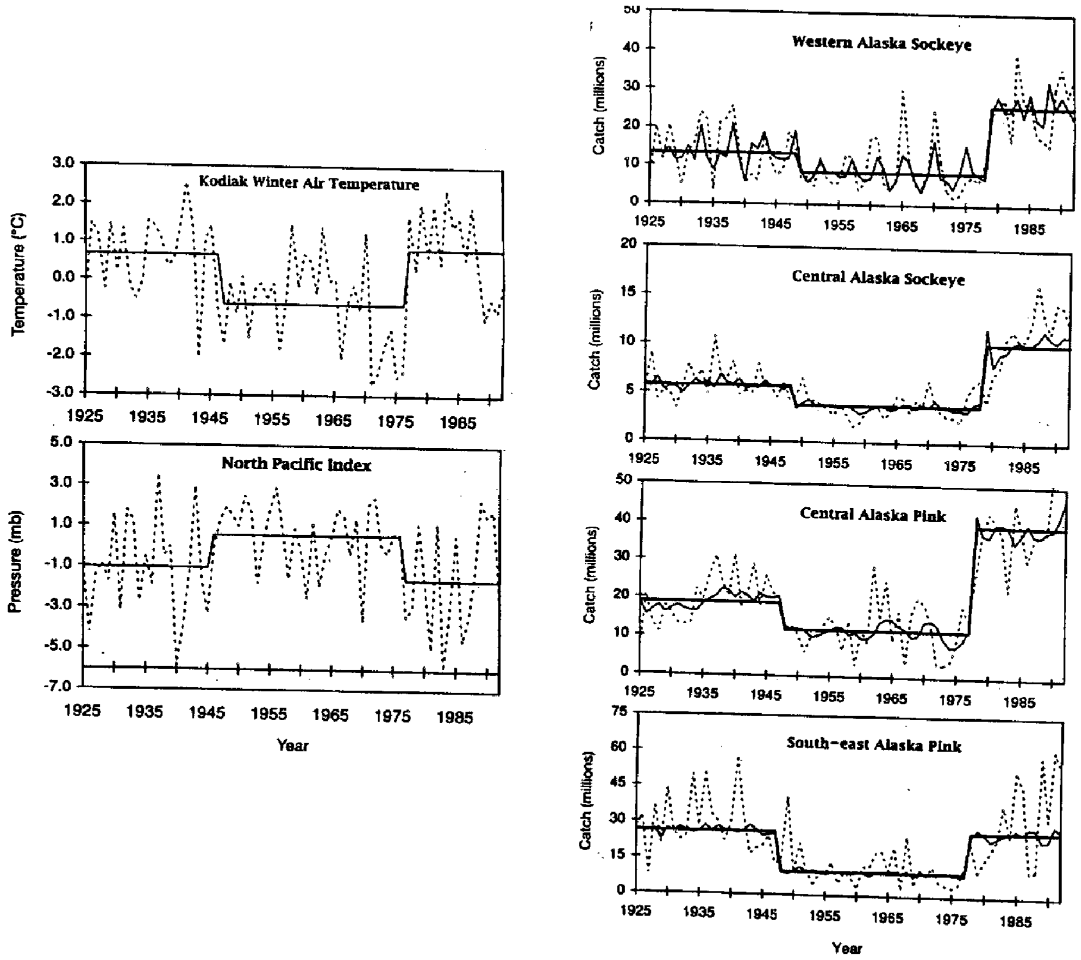

Figure 4. Results of intervention analysis showing environmental shifts (Kodiak Winter Air Temperature and North Pacific Index) and the shifts in catch of sockeye and pink salmon from the North Pacific. (from Francis and Hare, 1995)

species of interest for U.S. GLOBEC in the North Pacific would be salmon, pollock, herring, the dominant zooplankton species (the copepods *Neocalanus, Calanus,* perhaps others; and the euphausiids, *Euphausia* and *Thysanoessa*), and marine mammals (northern fur seals, harbor seals, perhaps sea lions) and bird predators (cormorants, murres, alcids, and others). Within the salmon, we emphasize process studies involving those with the shortest fresh water residence, in order to highlight the oceanic causes of mortality and growth. Off Alaska, these would be the pink and chum salmon. The retrospective and monitoring activity should make use of as many salmon species as data allow, using differences in life cycles (ocean and freshwater residence times, migration pathways, diet differences) to provide additional information.

Coordination with Other Programs

The salmon studies proposed below nicely complement other studies which focus on salmon populations in the Gulf of Alaska. The Ocean Carrying Capacity Program (OCC) being conducted by the AFSC Auke Bay Laboratory has two goals: "to describe the role and spatial distribution of salmonids in the marine ecosystem, and to test for density dependence in the growth rate of salmonids during various periods of ocean residency". They have selected the coastal marine phase of juvenile salmonids as the focus for this research. The investigation includes (1) broad-scale surveys and satellite observations to describe the distribution of juvenile salmonids and their environment; (2) process studies; (3) bioenergetic modeling of juvenile salmonids, which will be enhanced by otolith-marked pink, chum, and sockeye salmon from Alaska, British Columbia, and Washington; (4) studies of trophic dynamics, diet and prey selectivity; and, (5) use of genetic stock identification methods to monitor the location of juvenile salmon along the coasts of British Columbia and Alaska. Long-term patterns of growth and abundance of salmon and other species will be evaluated using (6) retrospective analysis of scales and otoliths and analysis of sediment layers.

Another program of relevance here is the Sound Ecosystem Assessment (SEA) program (funded by the Exxon Valdez Oil Spill Trustees), which is an investigation of the Prince William Sound (PWS) marine ecosystem, with a particular focus on understanding year-to-year differences in the success of pink salmon and herring. In 1994, surveys of PWS were conducted to measure plankton abundance, hydrography, currents and nutrients, with the thought being that interannual variations in these factors might lead to differing survivals of the target fish species. In addition to assessing prey abundance, studies are planned (or ongoing) to investigate the diets of the potential predator species. Related to this, the pink salmon hatcheries in PWS have begun to thermally tag the hatchery fish prior to their release. This will permit positive identification of salmon from the PWS hatcheries, and will enable better estimates of survival (from release to return) of hatchery-produced pink salmon. These survival estimates may be valid as well for native stocks, as demonstrated by recent investigations, where survival of hatchery and native pink salmon stocks from PWS showed similarly phased marine survivals, suggesting common factors (Cooney and Willette, 1996). Because of their short time in freshwater hatcheries, hatchery pink salmon are probably more representative of native stocks than would be true for other salmonids, which are hatchery-reared much longer.

The SEA study of PWS is important to future U.S. GLOBEC studies because it will improve our understanding of the sometimes complex food web of the nearshore region of the Gulf of Alaska. Depending on their relative sizes, each of the fish species (pollock, salmon, herring; see Fig. 5) is capable of preying upon all the others, including itself (cannibalism). During the productive season, say March to August, when large populations of copepods, including wintertime deep-dwelling interzonals, like *Neocalanus plumchrus* and *N. flemingeri*, develop on the shelf and in the Sound, zooplankton are a principal prey of juvenile pink salmon. The

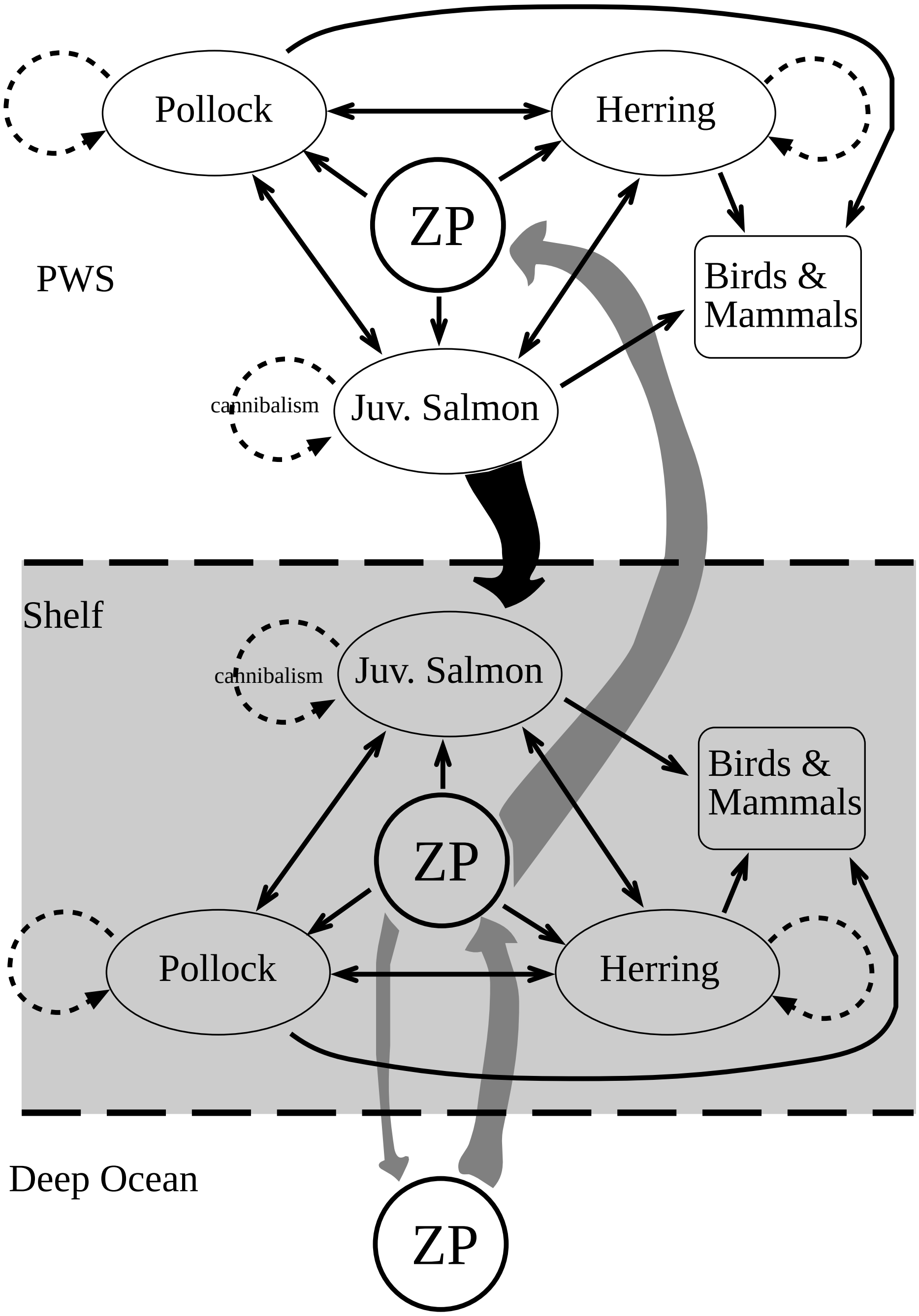

Figure 5. Schematic of the pelagic food webs within and on the shelf outside Prince William Sound, Alaska with herring, salmon (esp. juveniles), pollock, zooplankton (ZP), birds and mammals. Solid narrow arrows show trophic pathways between species. Dashed narrow arrows show cannibalism. Fat black arrow shows emmigration of juvenile salmon from PWS to the shelf. Fat gray arrows show exchanges of zooplankton between the deep ocean, shelf and PWS.

importance of immigration of these species from deep-water onto the shelf during the late spring is not known; they do not occur on the shelf during fall and early winter, so must be supplied either from deeper regions offshore, or from the deeper regions in the Sound, where they overwinter at 400-600 m depth. During the remainder of the year, the large interzonal copepods are not available to the juvenile fish; during those times other prey, perhaps euphausiids and other fishes, are the main diet. In addition to the piscivore predators, there are avian and mammalian predators on the juvenile fish of the coastal Gulf of Alaska. Figure 5 shows a schematic of a food web featuring juvenile salmon, their prey and their predators, which forms the basis of the U.S. GLOBEC program described below.

Coordination between components of PICES-GLOBEC and NOAA's FOCI program may result in better temporal and spatial coverage of important biological production processes in the Alaskan Coastal Current. FOCI has been studying biophysical variability affecting recruitment processes of the Shelikof Strait walleye pollock (*Theragra chalcogramma*) stock for the last ten years (Kendall et al., 1996). FOCI's studies have targeted the biophysical conditions that promote survival of pollock larvae. FOCI scientists developed a hydrodynamic model of the Western and Central Gulf of Alaska. This model could be extended to include a U.S. GLOBEC study area off PWS. Alternatively, U.S. GLOBEC scientists could develop hydrodynamic models that are compatible with the FOCI model. The FOCI program is currently focusing their research effort on the processes that determine the overall level of biological production within the Alaska Coastal Current. They are also conducting studies of the role of *in situ* production and transport in controlling the food supply for planktivorous fishes.

Monitoring Studies

We make the following recommendations with regard to monitoring activities in the subarctic Pacific:

1) **Continue or establish time-series** to address the following questions:

a) How does the Aleutian Low drive physical forcing? Specifically, how do variations in the strength and position of the low affect alongshore and cross-shelf transport, and the circulation in mesoscale features?

b) How does physical forcing affect the availability and production of prey and the abundance of predators of juvenile salmon in the coastal Gulf of Alaska? This might require observations of physical and biological parameters along a **few key cross-shelf transects** (sampled every other month, or more frequently if feasible). Bimonthly sampling is inadequate to resolve the dynamics of the shorter lived zooplankton that are potential prey of the juvenile salmon. The detailed transect data should be complemented with continuous time series ADCP, acoustics, bio-optics, and physics measured from a small number of moorings, to prevent aliasing of the data, and to capture large amplitude events that occur during the interval between transects.

c) How does physical forcing affect the production and availability of salmon prey as indicated by zooplankton in the open ocean (deep water of the Gulf of Alaska)? This question relates to the growth of salmon during their oceanic phase (H2 above).

We **recommend that several (we suggest 3) deep-water moorings be placed in the Alaskan Gyre**. These moorings should be located (1) off the shelf in deep water, but adjacent to the coastal region selected for detailed process studies; (2) near the center of the Alaskan Gyre; and, (3) at an intermediate location between (1) and (2). The intent is to use the data collected from these three moorings to monitor the abundance and distribution of potential salmon prey. The locations are suggested by the observations of Brodeur and Ware (1992) that zooplankton abundance increased most markedly over decadal scale periods along the margins of the Gulf of Alaska--more so than in the central Gulf. If an important feature of the decadal change observed by Brodeur and Ware is a shift in the distribution of zooplankton from the central to marginal regions of the gyre, then it is important for a U.S. GLOBEC study to include an effort to capture the transport of subarctic zooplankton to the coastal zone. Multiple moorings, spanning the central gyre to the margin, would provide the data necessary to document such shifts. The moorings should consist of mostly biological instrumentation, but with some physical observation capability. It is most important that this mooring be equipped to measure acoustic backscatter, preferably at multiple frequencies, to provide an estimate of zooplankton biomass (and perhaps size), and light and fluorescence sensors (to measure phytoplankton stocks). An appropriate bio-optical model could be used to estimate primary production from light and phytoplankton biomass estimates. In the Prince William Sound region, the three deep-water moorings would complement existing or planned moorings near Seal Rock on the shelf proper, and two moorings within PWS.

Ships of opportunity should be used to expand geographic coverage in the Alaskan gyre beyond that of the mooring locations. For example, it was noted at the workshop that ships routinely cross the gyre enroute from Valdez, AK to Hawaii. This would be a valuable route for towing a high-speed undulating instrument. There may be other routes as well.

2) **Develop methods to measure cross-shelf exchange, perhaps using chemical or biological tracers**. This should be an initial activity--to begin as soon as funding becomes available for a U.S. GLOBEC North Pacific study.

3) **Large-scale monitoring** is needed to evaluate how variability in atmospheric forcing and variability in the position and strength of the west wind drift affect the circulation and water mass characteristics of the Alaskan Gyre. This is needed to document the effects of these large-scale forcings on the productivity of the Alaskan Coastal Current, and on the distribution, growth and survival of salmon and their prey in the open ocean. Monitoring of the entire North Pacific Basin should be conducted as a coordinated multinational effort. We recommend that U.S. GLOBEC monitor the circulation and characteristics of the Alaskan Gyre and the bifurcation of the west wind drift as it nears North America by a **combination of remote sensing (including altimetry), a few strategically placed moorings and/or transects, and atmospheric models**. Temperature and salinity profiles of the Subarctic Basin could be obtained using PALACE floats. PALACE floats are programmed to sit at depth on a density surface (perhaps at 800-1000 m depth). Periodically, perhaps at weekly to biweekly intervals, they collect high-quality temperature, salinity and pressure profiles as they rise to the surface. They remain at the surface (order 16-32 hours) long enough to transmit their hydrographic data via ARGOS transmitters. During their time at the surface, they also provide data on surface currents in a Lagrangian sense. Their estimated lifetime is two years.

Retrospective Studies

The overall goal of the retrospective studies is:

Carefully examine ecosystem or population shifts across the North Pacific Basin in relation to interdecadal or interannual climate variability, especially examining synchrony across populations.

Rather than recommend specific retrospective studies, the working group brainstormed potential data types that might be suitable for use in retrospective studies. We list them below as either biological or physical data sets, realizing that the true power of the retrospective studies will be in interfacing the two types of data sets.

Biological Data Sets

- Birds--life history parameters
- Marine mammals--life history parameters
- Fish--strength of year class; growth and survival; the group noted that it was important to include species other than salmonids in this aspect (e.g., halibut, sablefish, others)
- Salmon scales collected and analyzed since the early 1900s--perhaps organize and fund a workshop, since this data has been collected by many countries bordering the North Pacific
- Zooplankton abundance
- Paleoceanographic fish scale records

Physical Data Sets

- Wind Stress
- SST
- GAK1 Data Set from near Prince William Sound
- Hydrographic data sets
    - COADS, mixed layer depth
    - Trans-Pacific Cruises
    - Drifter data sets
- Coastal sea level
- Coastal precipitation and river runoff
- Sea level pressure
- delta-O18
- Atmospheric models to hindcast storms, etc.

Modeling Studies

Overall, the modeling goal of a U.S. GLOBEC North Pacific program is to develop physical basin scale models of the North Pacific that include equatorial dynamics (to capture the ENSO connection), and to couple these with detailed regional-scale coupled biological-physical models. Specifically, we recommend that models of four types be developed:

1) A physical model of the North Pacific that has the ability to be coupled with larger scale atmospheric models to allow hindcasting.

2) A basin scale "gyre and coastal" coupled biophysical model that resolves the details of exchange of water and organisms between the coastal shelf and deeper oceanic waters.

3) Regional nearshore biophysical models. These should be capable of including coastal transport processes and detailed biology, including food web relations and organism behavior.

4) Detailed biological models, with perhaps less physical detail. An example might be bioenergetic models of juvenile salmon, predator relations, seasonal prey switching behavior, or nearshore food web dynamics for several different environmental scenarios.

Process Studies

Intensive process studies should be held in one or more regions surrounding the repeat transects and moorings comprising the monitoring system. These sites should have good historical time series and ongoing ancillary data collection (winds, tide gauges, biological sampling, fisheries records, etc.).

Following discussions at the workshop, the working group recommends that the process-oriented investigation of the food web shown in Figure 5, focusing particularly on pink salmon, their prey and predators, be conducted on the shelf region outside Prince William Sound in the northern part of the Gulf of Alaska (see Figures 6a, b). Prince William Sound has large wild and hatchery-released stocks of pink salmon. Over the course of the year, approximately 450 million hatchery fry are released with thermally marked otoliths. These join an about equal number of wild out-migrants from adjacent natal areas. The marked fish can be used to estimate survival from the time of release to 1) the fish exiting the Sound, and 2) to hatchery return. These hatcheries are the only ones in this region using thermal marking, thus it provides positive identification of the pink salmon source. In addition, the thermal marking of fry in PWS hatcheries is being supplemented in 1996 and perhaps 1997 by continuing to wire-tag as well about 1% of the released fry. The wire tags are being used to validate the thermal marking technique. Although speculative at this point, it would be interesting to involve the hatchery operations of the PWS region in "experimental manipulations" of the ecosystem. This could be achieved either by varying the timing of release of hatchery fry, their size at release, or the number released. Monitoring of the dynamics of the nearshore food web in response to such manipulations might provide powerful insight into the interactions occurring in the ecosystem. Whether the hatcheries of the system would be interested in conducting such experiments remains to be investigated.

The SEA program is currently studying the dynamics and interrelationships shown in the food web of Figure 5 in PWS itself. We propose to conduct similar studies, over the much larger region on the shelf (outside PWS), ranging from approximately 143°-150°W. The Alaskan Coastal Current, which dominates the circulation on the shelf in this region flows from east to west in this region (Fig. 6b). The box delimiting the study region is approximately 300 km alongshore and 150 km in the cross-shore direction. There is some earlier data from the OCSEAP (Outer Continental Shelf Environmental Assessment Program) program conducted during the mid-to-late 1970s (Hood and Zimmerman, 1986). The westernmost transect shown on Figure 3 is the Gulf of Alaska (GAK) line. Significant physical records exist for the line, with the innermost station (GAK1) having been sampled frequently since 1970. A hydrodynamic model of flow into, within and exiting PWS is being developed within the SEA program. The mechanisms responsible for seeding of the Sound with *Neocalanus* populations from offshore is of interest to the SEA program. *Neocalanus* intrudes along with the other interzonal copepod, *Eucalanus bungii* (Cooney, 1986), demonstrating a connection with the adjacent shelf/ocean. A U.S. GLOBEC investigation focused on the region identified above will elucidate the mechanisms by which these interzonal copepods, which overwinter in the deep-water off the shelf, recruit onto the coastal shelf (U.S. GLOBEC's interest) and into PWS (SEA's interest). There is a permanent eddy on the shelf, west of Kayak Island (Figure 6b), which may be important in determining residence times of some of the organisms on the shelf, even though it is "upstream" of PWS.

Since it is presently unclear how far to the west the salmon emigrating from PWS reside on the shelf in the Alaskan Coastal Stream before moving further offshore, we also recommend that studies sample for migrating juveniles further to the west, perhaps even into Shelikof Strait.

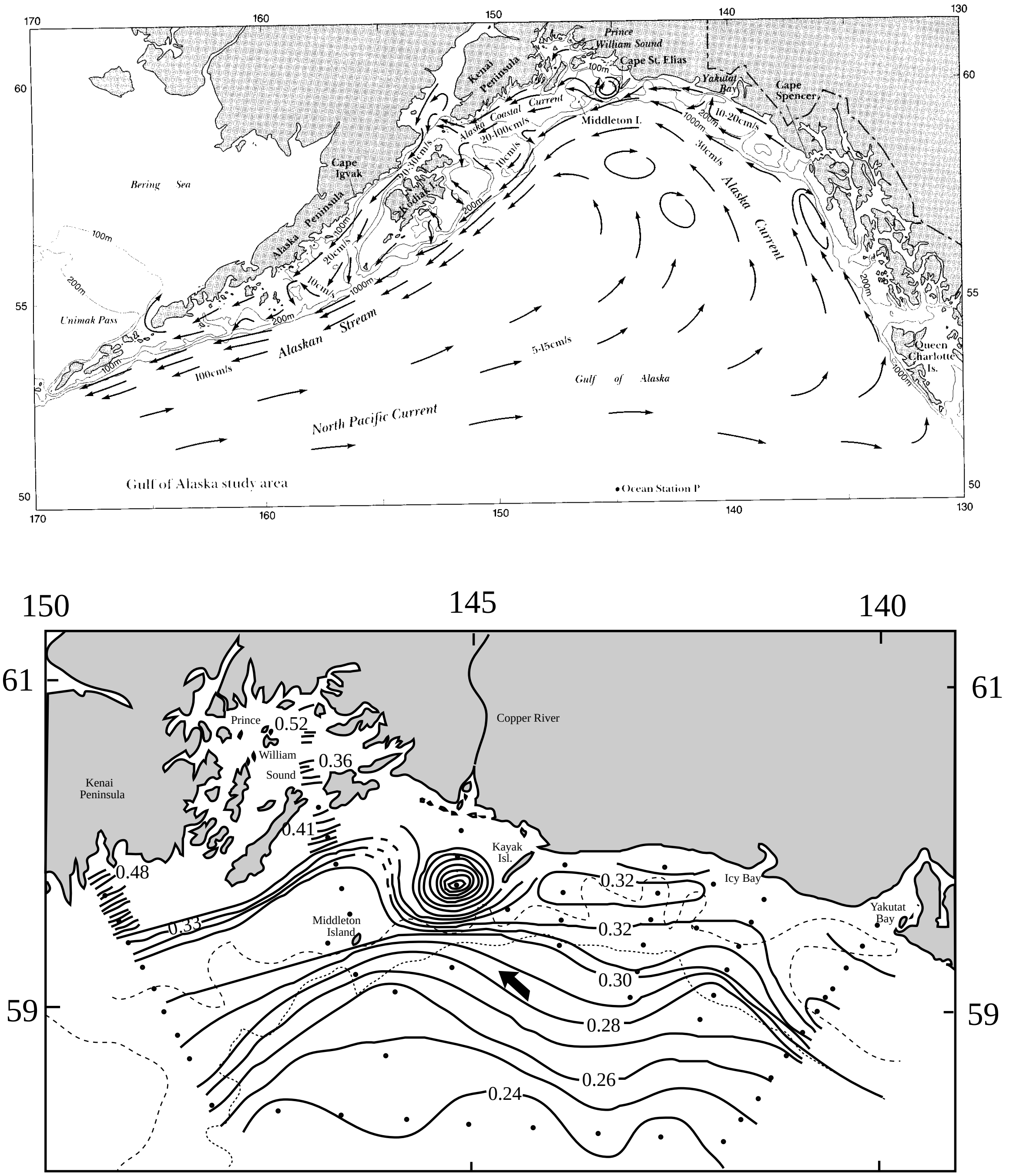

Figure 6. Top) Major currents of the Gulf of Alaska (from Reed and Schumacher, 1986); Bottom) the geopotential topography (ΔD, dyn m) of the sea surface (1/100 db) during September 1976 on the Alaskan Shelf outside of Prince William Sound. The 183 m and 1830 m depth contours are shown as broken lines. (redrawn from Reed and Schumacher, 1986).

Information on juvenile pink salmon residence time in the shelf environment is very important because predator (esp. adult pollock and birds) abundances in the Shelikof Strait region, north and west of Kodiak Island, are orders of magnitude greater than they are immediately outside of PWS. If the juvenile salmon pass through Shelikof Strait, depending on the time of the year, mortality may be very high. Directed surveys should be used to document salmon abundances, migratory pathways, and the abundances of predators during their time on the shelf.

Specifically, the question that U.S. GLOBEC proposes to address in process-studies of this region is:

> **What are the processes (biological and physical) that determine growth and survival of juvenile salmon in the coastal zone?**

It was evident from the discussions that the important season for this study was the productive season, which runs from ca. March to October. We recommend that three cruises be conducted each year of the study: during March, July-Aug. and Sept.-Oct.

The March cruise is used to document the conditions of the coastal environment just prior to the spring bloom. This is the period when the diapausing copepod populations are waking up, reproducing immediately at depth, or returning to the surface and reproducing, and perhaps transiting onto the shelf. *Neocalanus plumchrus* and *N. flemingeri* adults reproduce at depth (>400 m) and then die. The eggs, nauplii and early copepodites arrive ahead of the spring bloom—about the first of March. They are probably sustained on yolk reserves (early nauplii) and the ability to feed on microheterotrophs before the bloom is triggered in early April. Conversely, *Calanus marshallae* and *Eucalanus bungii* return to the surface in spring as adults or C_5 stages where they first feed, then reproduce. Broods of *C. marshallae* and *E. bungii* occur in the upper layers after maturing *Neocalanus* C_5 stages leave the surface in late May and June. In PWS, the important point is that *Neocalanus* produces a mid-spring bloom of biomass that corresponds closely to the timing of the outmigrating fry (Cooney et al., 1995). It is unknown what kinds of forage the fry consume later over the shelf when they leave Prince William Sound. This should be a major focus of the two later cruises.

The July-August cruise is just before the principal outmigration of the pink salmon from PWS onto the shelf proper, and is primarily intended to determine the abundance, distribution, and species composition of the zooplankton populations. These zooplankton are important in the diet of the pink salmon, but also of other potential competitors and predators, such as the pollock and herring. In a sense, this survey will determine the species composition of the prey when the juvenile pink salmon exit PWS and enter the shelf system. Sampling on this cruise will also establish the identities and abundance of competitors and predators of juvenile salmon.

The September-October cruise is during the period when the juvenile pink salmon are in the coastal environment (outside PWS) and will focus on measuring their growth and survival, as it is impacted by the trophodynamics shown in Figure 5, and by physically forced variability.

Although the focus of the study is on the salmon, their zooplankton prey, and their competitors and predators, observations during the process studies should also include nutrient concentrations and phytoplankton concentrations, to the extent possible. These fields will provide some understanding of the lower trophic levels of the food web. The combination of strong buoyancy inputs and downwelling-favorable winds should inhibit upward motion and lead to low nutrient concentrations after any spring bloom. Thus, there is a special interest in how and where vertical fluxes of nutrients may be found in coastal downwelling systems, which have been much less frequently studied than upwelling systems.

Specifically we recommend the following studies:

1) **broad-scale surveys of the environment** using SEASOAR or similar technology to provide the physical context and map some biological parameters (using fluorescence, multiple frequency acoustics, and optics) for the entire 150 x 300 km region. It was estimated that, weather permitting, this survey might take 5-7 days of ship time. Hotspots in the acoustics or bio-optics should be sampled using conventional multiple opening and closing (e.g., MOCNESS) nets to provide specific information on the prey field. Acoustics should be used to measure the density of salmonids and other fish species.

2) **diet of juvenile salmonids and competitors and predators**; these might consider differences in the availability of different prey types, and effects of mesoscale variability.

3) **identify and estimate abundance of predators on juvenile salmon**; this would include other fish, birds and mammals. This may require directed studies encompassing a larger region, perhaps including Shelikof Strait, than some of the broad-scale surveys (1 above).

4) related to (3), **determine the predation rate of various predators on juvenile salmon**

5) **determine growth rates of juvenile salmon** during their residence in the coastal environment.

In the Sept.-Oct. cruise, items 2, 4, and 5 might be studied in a Lagrangian sense by deploying one or more drifters and sampling physical and biological conditions semi-continuously along the drift trajectory for up to one week. This might be repeated multiple times during a cruise. Finally, a second Eulerian survey (the first done at the beginning of the cruise) would be conducted of the entire region prior to the end of the cruise.

Ideally, the above [still rather sketchy] program would provide information on 1) the prey density, distribution and availability to the juvenile salmon; 2) the abundance of juvenile salmonids and other fish; 3) the diet of the fish species, especially juvenile salmon; 4) the role of birds and mammals as agents of juvenile salmon mortality; 5) growth rates of juvenile salmon during their residence in the coastal environment; and 6) the physical environment. These studies will have to be coordinated with estimates of return rates (survival) of hatchery released fish (obtained from the hatchery, and fishery collection of thermally marked fish), and with estimates of growth determined from analysis of scales and/or otoliths from fish returning to the hatcheries, captured by the fishery or collected in research collections. Because pink salmon have a short life span (2 years) and a short freshwater residence period (i.e., they enter the marine environment at a young age and small size), they are more likely than the other salmon species to have survival or growth rates impacted by interannual or interdecadal variability in coastal conditions.

Although the coastal region off Prince William Sound was selected as the focus for a U.S. GLOBEC study, there are a number of other programs that are currently examining or planning to study aspects of the salmon populations of the eastern North Pacific. The entire coastal strip along the eastern and northeastern Gulf of Alaska constitutes a possible migration path for juvenile salmon from the lower latitudes. The OCC program will sample a large part of this region and results from that study should be taken into account in designing the final sampling for the monitoring and process studies. The Canadian GLOBEC program will probably provide data from around Vancouver Island. Transects off northern California, Oregon and Washington may be supported through the NOAA/COP Northwest Pacific Regional Program. Dedicated process studies around each monitoring site would test the generality of the results from the primary site offshore of Prince William Sound. Whether these monitoring and/or process study sites can be maintained depends on the level of funding for the U.S. GLOBEC activities in the Alaskan Gyre and California Current, as well as other sources of funding. Some forethought is necessary now to coordinate U.S. GLOBEC salmon studies with other salmon studies, including those undertaken by PICES, OCC, Canada GLOBEC, and other NOAA/COP programs in the region. This coordination is essential in providing results which can be interpreted and generalized to both a) large (basin) - scale processes, and b) other salmon species.

Bering Sea Program

Working Group Members: Vera Alexander, Ric Brodeur, Anne Hollowed, James Ianelli, Thomas Loughlin, Tom Powell, Alan Springer, Phyllis Stabeno, Trey Walker, and Warren Wooster

Program Rationale

The biological richness of the large shelf and marked similarities in biophysical processes to those found in other large marine ecosystems provide compelling reasons for a U.S. GLOBEC program in the eastern Bering Sea. Annual variation of solar radiation, atmospheric conditions, ice cover and water column structure fueled by a flux of nutrient-rich slope water results in one of the world’s most prolific ecosystems (Niebauer et. al. 1990). Primary production over the shelf often begins with a bloom associated with ice-melt (Walsh et. al. 1989) and a "greenbelt" of annual production (>200 gC m^{-2}) occurs over the outer 200 km of the shelf/slope (Schumacher and Reed 1992). The accompanying zooplankton production supports vast populations of migratory marine mammals, birds, fish, and shellfish. The pollock fishery constitutes one of the largest single species fishery in the world and the run of sockeye salmon into Bristol Bay, Alaska, is one of the world’s largest (45 million adult salmon predicted for 1996). Shellfish and fish harvest from the region represented 40% of the annual U.S. commercial fish harvest in 1994.

The physical and biological characteristics of the Bering Sea lend themselves to comparisons with other world oceans. The Bering Sea shares several similarities to the Barents Sea ecosystem off the Coast of Norway (Schumacher 1987). The opportunity to draw comparisons between northern latitude seas could be particularly fruitful given the existence of the ICES Cod and Climate program. Comparisons of climatic regimes between the Barents Sea and the Bering Sea suggest that teleconnections exist that produce oscillating periods of low or high atmospheric pressure that persist for 6-12 years. Both regions are heavily influenced by seasonal ice coverage that is directly linked to atmospheric circulation. Like the Barents Sea, the Bering Sea ecosystem is dominated by three pelagic fish species groups [gadids (cod or pollock), herring and capelin] and a large demersal flatfish population. Likewise, the two regions have historically supported large pinniped populations.

The Bering Sea ecosystem also shares many notable similarities to Georges Bank, the focus of an ongoing U.S. GLOBEC program in the Northwest Atlantic. Fluctuations in the boundary location of two major air masses in both regions effects the physical characteristics of the ecosystem by influencing winds, advection, and air and sea temperature. Like Georges Bank, the Bering Sea exhibits readily identifiable physical features that directly influences the distribution of marine fish (i.e., the cold pool in the Bering Sea, bank circulation in Georges Bank). Similar to Georges Bank, tidal currents play an important role in both mixing and generation of residual flow at frontal features (Coachman 1986). Both regions historically supported large populations of commercially important gadids [i.e., Pacific cod (*Gadus macrocephalus*), walleye pollock (*Theragra chalcogramma*), Atlantic cod (*Gadus morhua*), haddock (*Melanogrammus aeglefinus*)] which consume similar zooplankton genera (*Calanus* and *Pseudocalanus*) during early life stages. Research on the Bering Sea ecosystem provides an opportunity for comparative studies on the response of copepod and gadid populations to changes in physical regimes in two separate but somewhat parallel regions. Both ecosystems are seasonal feeding grounds for migratory pelagic predators: Atlantic mackerel (*Scomber*) in Georges Bank and Pacific salmon (*Oncorhynchus*) in the Bering Sea.

Physical Environment

The important physical features of the Bering Sea are described in some detail in U.S. GLOBEC Report 15 (U.S. GLOBEC, 1996). The following features are particularly relevant to this implementation plan. We propose a program focused on six habitats or biophysical domains on the broad, shallow eastern shelf with the outer shelf and upper slope forming a seventh habitat (Fig. 7). Across the shelf the domains are separated by a sequence of frontal systems: shelf-break, middle, and inner or structural front. Circulation over the basin is characterized by counter-clockwise flow with an eastern boundary current (the Bering Slope Current at the shelf edge) (Fig. 8). Similar to conditions at Georges Bank, tidal currents play an important role in generation of the two shoreward fronts by mixing and generation of residual current by interaction with topography. Over the middle shelf, mean currents tend to be insignificant, whereas, moderate mean flow follows the bathymetry toward the northwest over the outer-shelf. Alaskan Stream water flows into the Bering Sea from the North Pacific primarily through Near Strait, Amchitka Pass and Amukta Pass (Fig. 9). Over the shelf, seasonal ice cover greatly influences currents and water property distributions, particularly that of temperature. Ice cover and its related processes determine the southeastern extent and magnitude of the "cold pool", a 40-50 m thick layer of water <2.0° C over the middle shelf, which persists throughout the summer (Fig. 10). The cold pool likely influences the distribution of biota on the shelf, and the ice extent influences the location and timing of the spring phytoplankton bloom.

Project Definition

The Bering Sea research program adopted the program design used in the Georges Bank U.S. GLOBEC program. The major focus of the program will be a study of the influence of physical processes on zooplankton populations with a principal interest in the role of secondary production in controlling the abundance of pelagic predators (Fig. 11). Following the PICES/GLOBEC research plan, the Bering Sea program explicitly focuses on the question of climatic effects on the carrying capacity of the ecosystem. Thus, the U.S. GLOBEC scientific program in the Bering Sea is designed to address top down and bottom up controls in the ecosystem. The study will examine the following hypotheses:

1.) **Zooplankton production in the Bering Sea is primarily directly or indirectly controlled by four physical processes: advection, stratification, sea ice coverage, and water temperature (the extent of the cold pool).** Changes in the physical environment may directly influence zooplankton populations by altering their physiology, production, or distribution. Physical processes can also indirectly influence the amount of secondary production by influencing: annual primary production, floristics, or the timing of phytoplankton production events (trophodynamic phasing).

2.) **Zooplankton production is jointly controlled by physical processes identified in (1) and predation by higher trophic level consumers.**

3.) **Annual zooplankton production is primarily controlled by predation and interannual variability is controlled by the distribution and abundance of higher trophic level predators.**

Studies designed to examine these hypotheses will address several related questions:

I. What are the characteristics of climatic variability; can interdecadal patterns be identified; how and when do they arise?

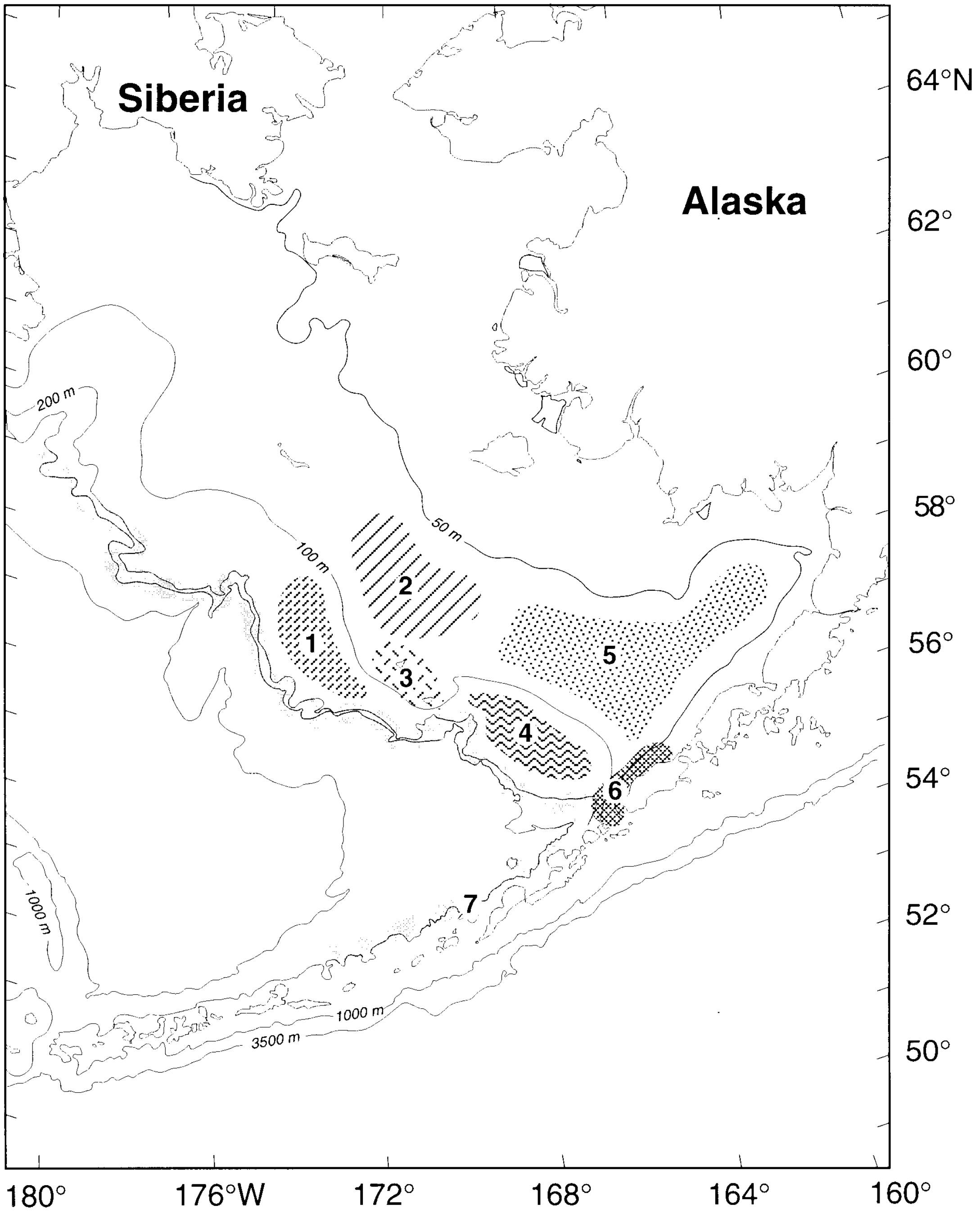

Figure 7. Habitats of the eastern Bering Sea: 1) Northwest outer shelf, 2) Northwest middle shelf, 3) Pribilof Islands, 4) Southeast outer shelf, 5) Southeast inner shelf, 6) Unimak Island, 7) Shelf Break.

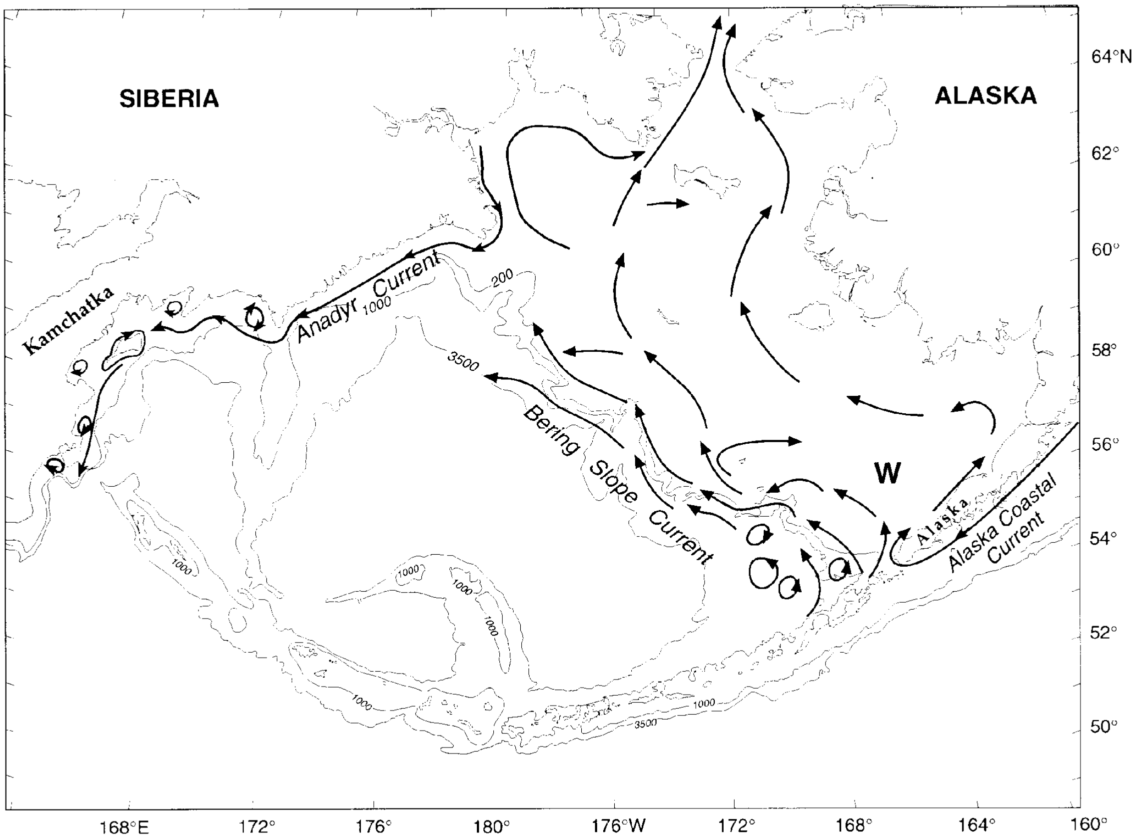

Figure 8. Location of major currents in the Bering Sea. (from Schumacher and Stabeno, in press)

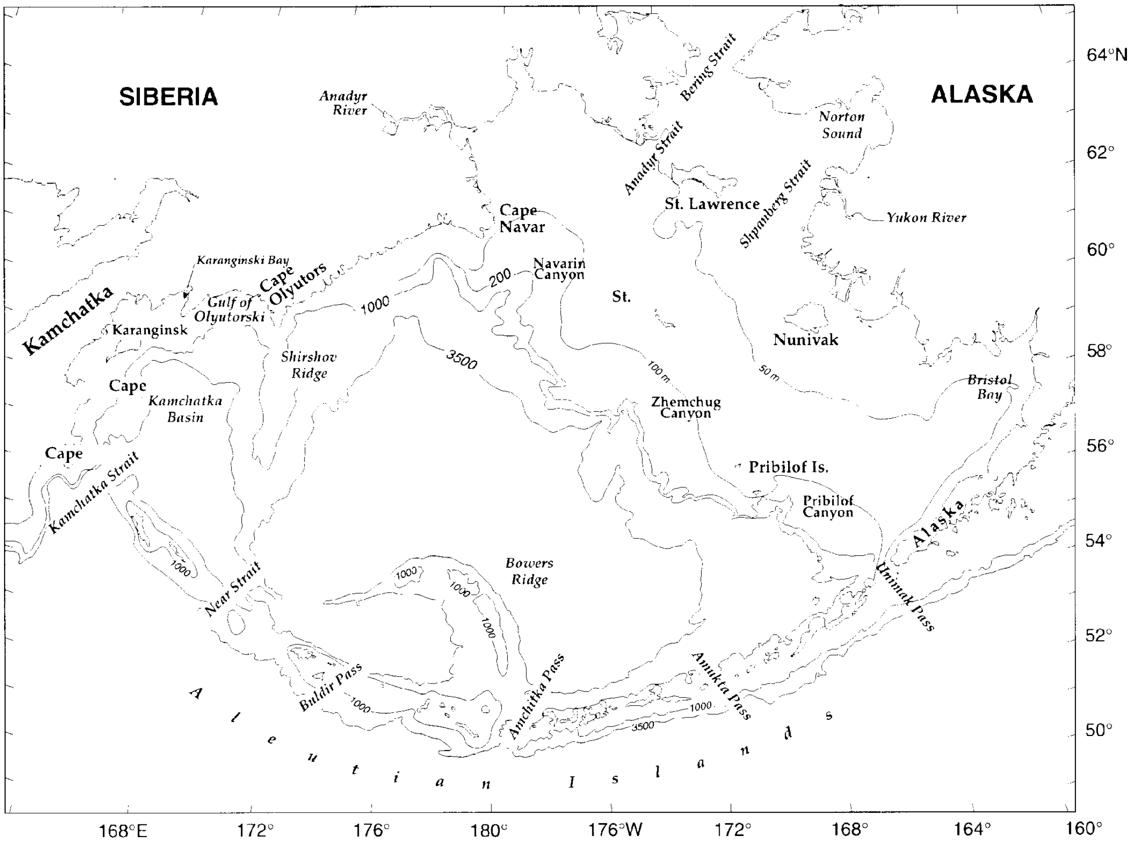

Figure 9. Depth contours and major topographic features of the Bering Sea and Aleutian Islands. (from Schumacher and Stabeno, in press)

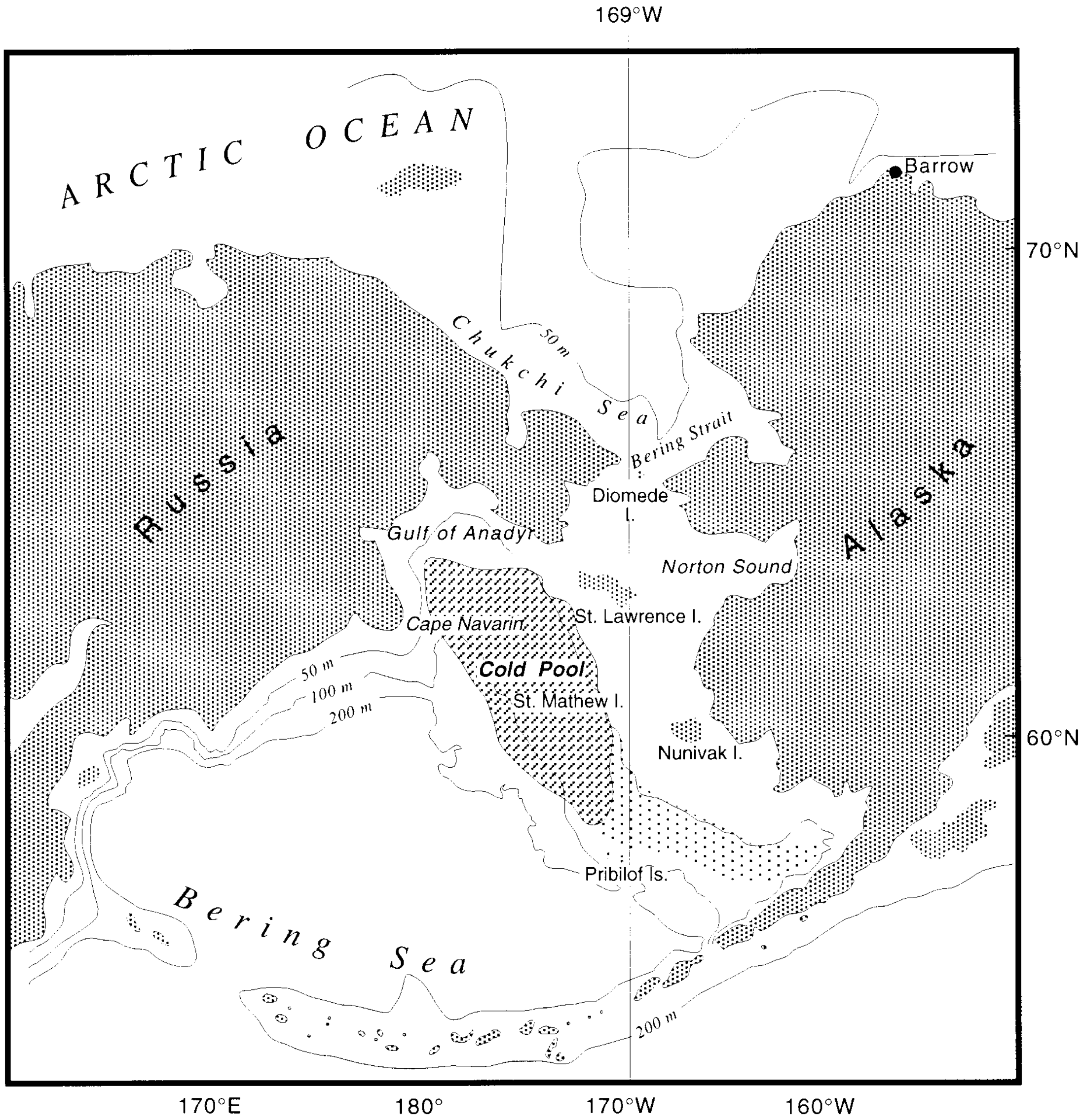

Figure 10. Location of the cold pool in the Bering Sea. (from Wyllie-Echeverria, 1995)

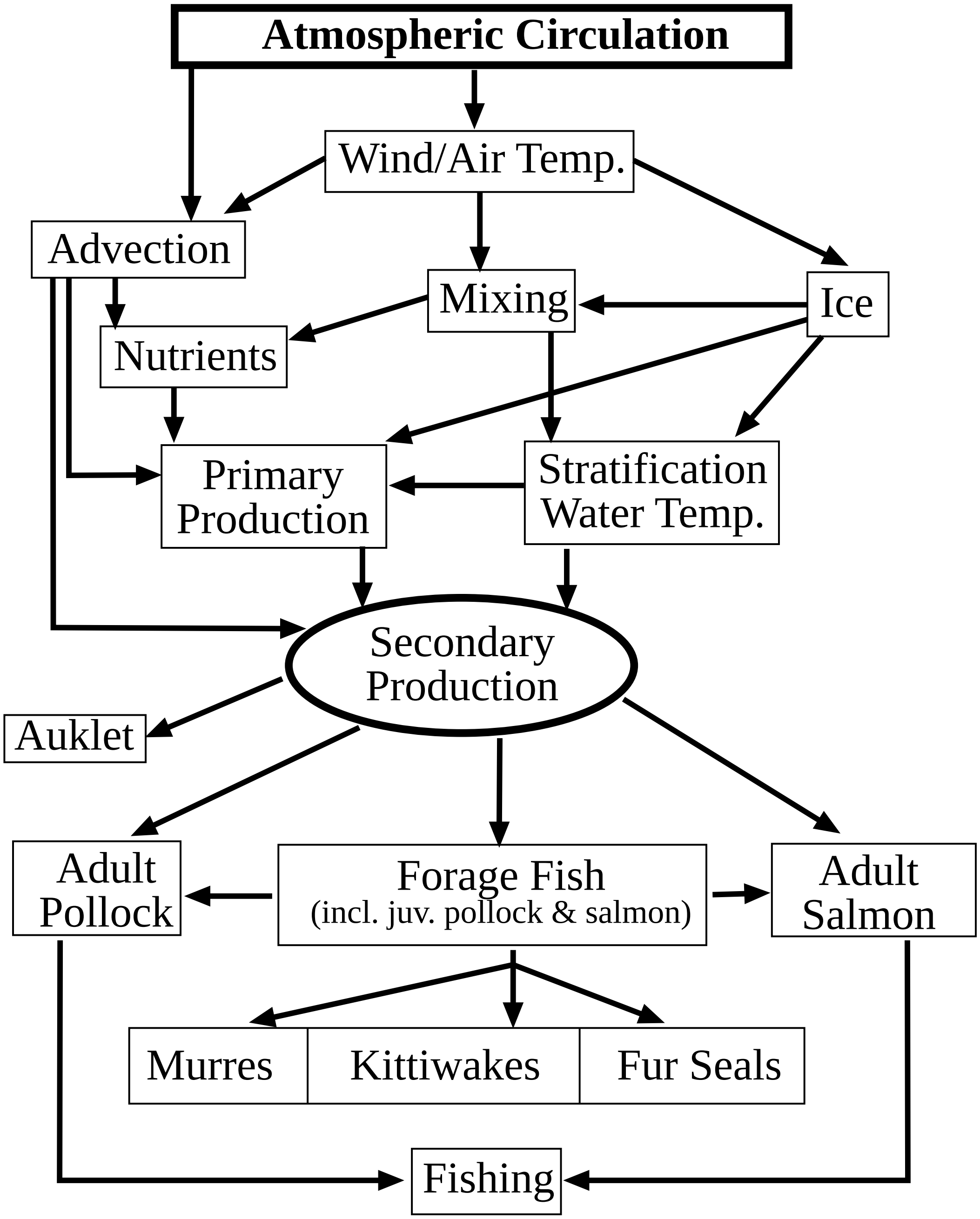

Figure 11. Schematic representation of the major physical and biological factors influencing secondary production in the Bering Sea that could be examined in a U.S. GLOBEC study of the Bering Sea.

II. How do changes in atmospheric forcing influence the physical dynamics of the Bering Sea?

- II.a) How does physical forcing affect ocean temperature?
- II.b) How does physical forcing affect the timing of the formation of the cold pool?
- II.c) Does variability in the strength and position of the Aleutian low pressure cell influence sea ice or the cold pool?
- II.d) How do physical factors influence the mixed layer depth (MLD), mixed layer temperature (MLT), retention time scales (eddies), turbidity, and shelf/slope exchange?

III. How do life history patterns, distributions, vital rates, and population dynamics of key species respond directly and indirectly to climate variability?

- III.a) Is there a relationship between the cold pool and larval survival or recruitment of important prey species?
- III.b) 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?
- III.c) Is there a relationship between the cold pool and larval survival or recruitment of important prey species?

IV. How do higher trophic level species respond to climate variability? Are there significant intra-trophic level and top-down effects on lower trophic level production and on energy transfer efficiencies?

- IV.a) How variable is the overall productivity of the Bering Sea?
- IV.b) Given this change in productivity, has the overall carrying capacity (K) also changed for high trophic level carnivores?

Key Species

Target species were chosen to represent key elements of the holoplanktonic assemblages on the Bering Sea shelf and their pelagic predators. The program focuses on copepods and euphausiids, their pelagic prey and predators. Since the main question focuses on how climate affects the carrying capacity, the program targets the dominant species within the ecosystem. Additional criteria used to select key species included the following:

- Likely to be impacted under hypothetical climate change scenarios.
- Economically or ecologically important
- Evidence that life history variability is linked to environmental variability.
- Widely distributed, providing opportunity for regional comparisons.
- Life-histories and/or ecological interactions representative of many other species.
- Demonstrated evidence of long-term shifts in abundance.
- Distribution associated with physical features and/or faunal boundaries.
- Analogous species occur in other ecosystems.

Based on these criteria, the following key species were identified for the Bering Sea program.

Zooplankton: Copepods: (*Calanus marshallae, Neocalanus cristatus, N. plumchrus, Pseudocalanus* spp., and *Oithona* spp.); Euphausiids (*Thysanoessa longipes, T. inermis, T. raschii)*

Seabirds: Least auklet (*Aethia cristatella*)

Pelagic Fish Stocks: walleye pollock, Pacific herring (*Clupea harengus pallasi*); sockeye salmon, pink salmon, chum salmon

Non-Commercial Forage Fish: capelin (*Mallotus villosus*), sand lance (*Ammodytes hexapterus*), myctophid and bathylagid fishes

Other Invertebrates: "Jellyfish" (scyphozans and hydrozoans), cephalopods, and chaetognaths

Several other important species/species groups were identified because they may play an important role in controlling the abundance or distribution of key predators on zooplankton or might be sensitive indicators of changes in abundance or distribution of key planktivores. These species include: Northern fur seals (*Callorhinus ursinus*), kittiwakes (*Rissa*), murres (*Uria*), piscivorous flatfish, Pacific cod (*Gadus macrocephalus*).

Retrospective Studies

A key problem is to establish the pattern of natural variations, both in physical forcing and in ecosystem response, over as long a time period as possible. That can only be done by looking backward over the period when suitable physical and biological data are available. The approach is known as retrospective analysis and is a necessary precursor for hypothesis formulation, modeling, process studies, and design of monitoring systems. Such studies were instrumental in identifying the so-called regime shift in the late 1970s, both in the nature of physical changes and responses in primary and secondary productivity and in recruitment and abundance of certain fish stocks.

Comprehensive retrospective analyses require reasonably long time series (e.g., up to 100 years) of data on key ecological variables. Unfortunately, such data on key variables rarely exist, so surrogate data are often used. For example, sea surface temperature data are common and have been used as proxies for scarce data on mixed layer temperature. Similarly, sea level data have been used as proxies for direct measures of circulation. Biological data are typically rarer than physical observations—often the longest time series of biological data result from total catch by commercial fisheries. Such fishery data provide only crude estimates of abundance, but that may be all that is available. Data from archaeological and paleoceanographic studies (such as isotope ratios and fish scale deposits) typically cover longer time horizons and represent a potentially useful alternative for reconstructing environmental conditions and biological production.

Long-term historical time series of biological data exist for two of the key fish species identified in this program: walleye pollock and sockeye salmon. Biological samples for the Bristol Bay sockeye salmon represent one of the longest time series collected for any population of Pacific salmon. The migratory pathways and summer feeding grounds of Bristol Bay sockeye salmon are well documented. The walleye pollock stock has been studied intensively for the last 20 years and fisheries data for some key indices (i.e., recruitment, and abundance) extend back 30 years.

Common approaches in retrospective analysis include various forms of correlation analysis and pattern matching. In all cases, methods of establishing relationships between physical and ecosystem variations must be examined critically before cause and effect are inferred.

Developing critical reviews and providing guidance on methods of retrospective analyses are an ongoing activity of several PICES scientific working groups.

Two reviews of the Bering Sea ecosystem were recently conducted by PICES and the Natural Research Council. These reviews summarize the current state of knowledge with regards to the Eastern Bering Sea ecosystem and recommend analyses of past abundance levels of key species and their spatial distribution. In particular, changes in spatial distribution and species compositions require review so that some idea of the variability is documented. Summaries on the historical feeding habits of the key species will also be important for studies of species interactions and trophic interactions.

Modeling

Physical modeling studies are needed in the Bering Sea U.S. GLOBEC program to diagnose and project the effects of climate change on physical features (e.g., currents, vertical structure, ice), to generate velocity and scalar (e.g., temperature, salinity) fields as a complement to field investigations, and to drive spatially-explicit biological models of the Bering Sea ecosystem. To serve such purposes, a model must have sufficiently small horizontal spacing to resolve inflows and outflows through passes, flows along submarine canyons that cut across the shelf, and mesoscale eddies which range in size from 20-200 km (Schumacher and Reed, 1992). Vertical resolution must be sufficient to allow decoupling of flow from topography under stratified conditions, to permit the development of appropriate shears when flow is baroclinically unstable, and to at least partially resolve boundary layers at the top and bottom of the water column. Ice must ultimately be included, or at a minimum parameterized as a surface buoyancy forcing, to generate the cold pool in appropriate years. Tides or at least tidal energy must be included in modeling efforts on the Bering Sea shelf.

The domain for the physical model is the eastern Bering Sea shelf, extending out into the Bering Sea basin, and including at a minimum, the Bering Strait, Unimak Pass, and Amukta Pass. The inflow from Amchitka Pass must also be considered. Grid spacing should be approximately 5 to 50 km, varying by location. Finest resolution should be employed near the Pribilof Islands, because of their special biological significance, and near Unimak Pass, to better capture the detailed structure of that inflow. Fine vertical spacing would be needed near the sea surface.

Knowledge of the temperature, salinity and velocity fields is crucial for understanding multiple trophic levels. Primary production depends on the interplay of light, predation, advection and vertical mixing, and varies widely in space. Both vertical and horizontal advection and diffusion supply nutrients, whereas excessive vertical mixing can deprive phytoplankton of adequate light.

Secondary production is in turn strongly dependent on the magnitude of this primary production. Species at higher trophic levels, such as pollock, can be strongly affected by the circulation field as spawned individuals are advected to food-rich or food-poor environments. Hydrographic features such as the cold pool may act to segregate predators from their prey (e.g., adult pollock from juveniles).

The physical models described above can be coupled with a suite of biological, biophysical and ecosystems models. Development of biological models should occur concurrently with development of the physical model. Four types of biological or biophysical models are recommended (See below). Linking outputs from each of these models will allow the examination of ecosystem level questions regarding top down or bottom up controls in determining pelagic production in the Bering Sea.

1) A spatially-explicit, individual-based model (IBM) of the early life stages of key fish species (e.g., walleye pollock and/or sockeye salmon smolts). This model should be coupled with a physical model, and eventually, with both lower and upper trophic level models (see below). Such a model could be used to examine hypotheses relating biotic (e.g., zooplankton prey production, predation, cannibalism) and abiotic (e.g., temperature, salinity, advective patterns, the role of the cold pool and fronts, climate change) factors to the population dynamics of key species.

2) A lower trophic model, a spatially-explicit Nutrient-Phytoplankton-Zooplankton (NPZ) model, should be developed to investigate questions of primary and secondary production as they relate to physical forcing and control by upper trophic level processes. As mentioned above, this model should also be coupled with the IBM.

3) A spatially resolved multispecies model of upper trophic levels, which focuses on adult pollock and sockeye salmon, their predators and competitors. This model would be useful in investigating hypotheses regarding bottom-up and top-down control of ecosystems processes, including the central issue of cannibalism as a major controlling factor in pollock population dynamics. This model may use physical forcing by the hydrodynamic model, lower trophic level input from the NPZ model, and may be coupled with the IBM in order to track the early life stages of key fish species.

4) An aggregated ecosystems model, which includes basic trophic components and a simple spatial structure. This simplified model would be intended primarily as an exploratory tool. Questions about the factors that might lead to shifts in the broad ecosystem structure of the Bering Sea, about net production ("carrying capacity") of the systems, and about the effects of climate change on ecosystem structure could be addressed with this type of model.

In addition to the above, specific biological models, such as one concerning the bioenergetics of juvenile stages of key fish species, and fine-scale biophysical models, such as one focusing on predator-prey interactions at fronts around the Pribilof Islands would be useful to examine areas of critical importance to the larger system.

Monitoring

The goal of monitoring studies is to acquire observations of physical, chemical and biological aspects of the environment to investigate interannual variability over an extended period of time. These time-series serve several purposes: 1) they provide the observational basis to develop indices either directly related to zooplankton success or to the success of their predators and prey; 2) they allow comparisons among habitats and years; and 3) they provide an environmental data base complimentary to modeling and process oriented studies.

The first objectives are to establish those aspects of the environment which indicate or significantly influence the status of zooplankton populations; and identify where critical or pulse-points of the system exist. This can be achieved using existing knowledge of the ecosystem augmented by retrospective and modeling studies.

In the southeastern Bering Sea, physical processes and topography results in several domains that provide different conditions/habitats for zooplankton and thereby are candidates for monitoring:

- The Bering Slope Current (BSC) and its upstream source, the Aleutian North Slope Flow (Reed and Stabeno, submitted) provide the seaward boundary of the shelf and bathes the outer shelf with heat, salt, nutrients and plankton. Further, this is the region where high primary (~365 gC m^{-2} yr^{-1}: NRC report) and secondary production (64 gC m^{-2} yr^{-1}) result in the feature known as the "Green Belt" (Springer and McRoy, 1996) (Fig. 7). The BSC originates as a flow along the north side of the Aleutian Island chain (Stabeno and Reed, 1994: Reed and Stabeno, 1994; Schumacher and Stabeno, in press). This region north of the Aleutian Islands is biologically important because salmon occupy this region during their summer feeding migrations. Transport through Amukta Pass augments this flow, influencing the subsurface thermal environment (Reed 1995) and generating eddies that can contain a high abundance of larval pollock (Schumacher and Stabeno 1994).

- The Pribilof Islands provide a natural laboratory to examine many aspects of the ecosystem. The nearshore structural front (Schumacher et al., 1979) and to a lesser degree the more seaward middle front are a focus for higher trophic level organisms (Springer, 1993; Kinder et al., 1983). Coincident variations in physical and biological characteristics are a marked characteristic around the islands (Napp et al., 1995; Brodeur et al., 1996).

- The Outer Shelf has features distinct from both slope and middle shelf habitats: for example, water column structure, amount/duration of ice cover, plankton community and carbon flux dynamics (Cooney and Coyle, 1982). Interannual variations in ice cover as great as 40% (Niebauer 1988) occur. Ice-edge melt initiates a phytoplankton bloom and an estimated 10-65% of the annual production can occur during melt-back (Niebauer et al., 1995). Winds, directly related to convective cooling, ice formation and transport, also have a profound impact on low-frequency horizontal kinetic energy (Schumacher and Kinder, 1983) and vertical mixing. Nitrate-uptake exhibits a nonlinear relationship to wind induced mixing; the timing of storms relative to the phase of the production system (i.e., respiration or nutrient limited period) is critical (Sambrotto et al., 1986). While ice and wind are dominant features of the entire shelf, they exhibit differences among the shelf habitats north and south of the Pribilof Islands.

- The Middle Shelf has a carbon cycle that tends to enrich the benthos rather than being utilized by the pelagic community as occurs over the outer shelf; there is a 10-fold larger infaunal biomass found here than on the outer shelf (Cooney and Coyle, 1982; Walsh and McRoy, 1986). Cooling by convection, ice cover and the resultant cold pool exert a momentous influence on the ecosystem, with impacts noted from primary production to distribution of adult fish (Niebauer et al., 1995; Wyllie-Echeverria, 1995; Ohtani and Azumaya, 1995).

- The Unimak Pass region is dominated by flow of Alaskan Coastal Current (ACC) water through the pass (Schumacher et al., 1982) which forms the major shelf-to-shelf connection between the Gulf of Alaska and the Bering Sea and provides a sizable fraction of the net northward flow through Bering Strait (Schumacher and Stabeno, in press). This region is a locus of pollock spawning (Hinckley 1987) and a pathway for fish and marine mammal migrations to and from the Bering Sea. The flow of slope water onto the shelf here provides a second source of nutrients and biota (Napp et al., 1996) that influence this habitat and may be important throughout the outer shelf habitat.

Instruments on existing moored platforms can provide single or multiple point time-series of atmospheric and oceanographic parameters, including: downwelling irradiance, wind, air and water temperature, salinity, nitrate, currents, calibrated acoustic backscatter, and detritus.

Satellite-tracked buoys and shipboard surveys expand the limited spatial scale of moored current, temperature and ocean color observations. The addition of efficient underway sampling during the ongoing annual bottom-trawl and tri-annual hydroacoustic surveys of the eastern shelf conducted by the AFSC provides an excellent opportunity to enhance the Bering Sea monitoring effort. Close coordination with ongoing Japanese research provides similar opportunities.

Technology

Technological advancements in bio-optical, acoustic, and chemical sensors may allow more refined and comprehensive sampling in both time and space. While some of these instruments may be commercially available, the need exists for development and/or application, of technologies for specific program tasks under the conditions imposed by the extreme subarctic environment. Further, the technological development needs to commence when this program starts so that a viable product results prior to when the program ends. At present, Acoustic Doppler Current Profilers (ADCP) with calibrated backscatter (Flagg and Smith 1989) are moored in trawl resistant cages. Using artificial intelligence and a profiling package replete with temperature, optical and sample collecting abilities, one can envision directly sampling zooplankton whenever dramatic changes occur in backscatter strength to provide ground truth.

Technologies also need to be developed for more direct biological applications. Theilacker et al. (1996) developed indices of the physiological condition and feeding of larval pollock in Shelikof Strait based on changes in molecular (biochemical), cellular and tissue characteristics. While these technologies may easily be transferred to larval pollock in the Bering Sea, similar development may be required for other zooplankton predators.

Process-Oriented Studies

The goal of any process study is the development of strong, testable hypotheses and the design of field/laboratory experiments to repudiate these hypotheses. The results of these studies should be used to augment or modify retrospective and monitoring studies, but they also will provide needed input, particularly biological rates, for modeling studies. The development and use of appropriate new technologies (rapid discrete and continuous sampling, and non-invasive techniques such as optical counters, acoustics, and remote sensing) is strongly encouraged and should be incorporated into any field sampling program. Moreover, U.S. GLOBEC encourages coordination with other U.S. and international research programs presently conducting process studies in the Bering Sea to further our advancement of knowledge and avoid duplication of effort.

Process studies should be focused on the key species and factors which lead to the production and control of these species. Process studies will ideally be conducted over several years to examine interannual variability and will include both a Eulerian-frame (fixed grid or moorings) and a Lagrangian-frame (tracking a patch or water parcel) approach.

Field studies will be conducted to examine the processes at the critical periods when they most influence zooplankton production and should occur at the appropriate temporal and spatial scales to elucidate the controlling mechanisms. Process studies fall into two broad space/time categories: small- and meso-scale. Meso-scale (10-100 km) processes include distribution and movements of plankton in relation to features that are stable (fronts) or predictable (eddies, ice extent, "cold pool") from year to year. Variability in large-scale physical forcing may be expected to affect the location and/or intensity of these features in different climatic regimes.

Meso-scale process studies will entail physical measurements from satellites, shore- or ship-based observations, and drifter/mooring-based sensors. Biological observations would involved repeated at-sea sampling or enumeration of zooplankton and their food or predators. Emphasis should be placed at "pulse points" that could be expected to vary the most interannually or in some way reflect the status of the Bering Sea ecosystem.

Small-scale studies (1 m-10 km) will examine elements that affect individual survival including diel vertical migrations, predator-prey interactions, growth, and mortality. These studies should utilize repeated sampling at one location or tracking a population for a period of time to allow continuous or repeat sampling. Some behavioral and physiological components may require controlled experiments using either ships, floating mesocosms, or shore laboratories.

Six cruises are recommended:

1. An early spring cruise (March-April). Process-oriented studies conducted during this cruise will examine meso-scale physical and biological conditions leading to the initiation of the spring bloom, and will provide an estimate of the timing and magnitude of the spring bloom. Vital rates of key primary and secondary producers will be monitored. Moorings and drifters will be deployed.

2. A mid- to late-spring cruise (May). Process-oriented studies will be devoted to studies of small-scale patchiness of zooplankton in relation to physical conditions, food concentrations and predator distributions throughout the diel cycle. Zooplankton collections will be taken during this cruise to examine growth and egg production rates for comparison to available laboratory-derived rates. Comparative samples will be collected inside and outside of the cold pool. Zooplankton food dependencies and feeding rates will also be determined.

3. A broad-scale cruise, conducted in the summer (June-July). This cruise will examine the abundance and distribution patterns of zooplankton in relation to predators and prey. Vertical and horizontal distributions of zooplankton and their predators and prey will be collected. Concurrent measurements of physical conditions will occur using ADCP and CTD casts. In some years cooperation with NMFS may augment this research effort.

4. A cruise dedicated to the main run of Bristol Bay sockeye salmon (end of June). Process-oriented work will focus on the food habits and growth samples of returning salmon in relation to prey availability.

5. Summer predator surveys (June-August). Meso-scale studies of prey selectivity and diel consumption rates of important predators will be examined to estimate predation mortality of the key species. Fine scale studies of the mechanisms attracting or concentrating zooplankton in some areas (fronts, eddies, vertical stratification) will be examined. The impact of large concentrations of predators (schools, flocks) on depleting food resources will be addressed. Regions near the Pribilof Islands are recommended as survey sites to facilitate studies of sea birds and marine mammal food habits. Surveys near Unimak Pass and the outer 200 km shelf/slope are recommended to examine salmon feeding behavior. Secondary study sites could be determined by coordination with the broad-scale cruise.

6. Fall cruise to retrieve moorings and conduct hydrographic surveys.

IMPLEMENTATION

Data Assimilation and Dissemination

Investigators must adhere to the U.S. GLOBEC policies regarding data management (U.S. GLOBEC Report 10; U.S. GLOBEC, 1994a).

Project Management

The U.S. GLOBEC Scientific Steering Committee (SSC) is responsible for determining the broad outlines of the scientific planning of a North Pacific program, and will serve as advisors of project goals, priorities and objectives. When U.S. GLOBEC initiates studies in the North Pacific, it is recommended that a Project Management Team (PMT) be established that will provide active leadership for the scientific conduct of the U.S. GLOBEC CCCC project. The PMT for the North Pacific CCCC program will be analogous to the management team (U.S. GLOBEC Georges Bank Executive Committee) established in the earlier regional U.S. GLOBEC program in the Northwest Atlantic. Members of the PMT will be determined after a program is begun in the North Pacific, but at a minimum the PMT should have representatives interested in and responsible for: a) retrospective and regional comparative studies, b) modeling, c) process-oriented research and d) surveys and monitoring. It may be advantageous to have a member of the North Pacific Anadromous Fisheries Commission on the PMT as well.

One of the duties of the PMT will be to coordinate U.S. GLOBEC studies in the North Pacific with studies of other nations in the region. This could be accomplished through the PICES-GLOBEC CCCC Implementation Plan Team (IPT). If possible, a member of the U.S. GLOBEC North Pacific PMT should serve on the PICES IPT. This person will be responsible for communicating U.S. GLOBEC research objectives and coordinating research activities on the international scale.

Coordination with Other Programs

Coordination with existing national and international research efforts will be required for this project. Concerted efforts to coordinate research with NOAA programs such as the Coastal Ocean Program Regional Studies, National Marine Fisheries Service, and Pacific Marine Environmental Laboratory should be a high priority. The U.S. GLOBEC PMT will be responsible for ensuring that this type of coordination occurs whenever possible.

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