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

U.S. GLOBEC Northeast Pacific Implementation Plan

U.S. Global Ocean Ecosystems Dynamics

Report Number 17

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U.S. GLOBEC

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This implementation plan (IP) was developed by the U.S. GLOBEC Scientific Steering Committee (SSC) during a series of meetings held during 1996. Hal Batchelder prepared an initial draft of this IP, compiled, incorporated and edited comments and additional text from the SSC and prepared the report for final publication. The members of the U.S. GLOBEC SSC during 1996 are Robert Beardsley, Paul Bentzen, Louis Botsford, Michael Fogarty, Dale Haidvogel, Eileen Hofmann, Anne Hollowed, Mark Huntley, Valerie Loeb, David Mountain, Peter Ortner, Thomas Powell (Chair), Stephen Reilly, Allan Robinson, James Schumacher, Ted Strub and Joseph Torres. The U.S. GLOBEC SSC thanks the many scientists that actively participated in several earlier U.S. GLOBEC workshops, and contributed to earlier U.S. GLOBEC Reports on the California Current System (U.S. GLOBEC Reports No. 7 and 11) and the Subarctic North Pacific (U.S. GLOBEC Reports No. 15 and 16). Many of the ideas in this implementation plan were first described in those earlier reports. The SSC members of the Coastal Ocean Processes (CoOP) program, especially Mike Roman, Ken Brink and Bob Smith, also contributed valuable ideas to this plan. Finally, special thanks go to Ted Strub and Anne Hollowed for their unflagging committment during this lengthy process.

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Executive Summary

U.S. GLOBEC Rationale in the Northeast Pacific

On a wide range of time scales (from seasonal to interdecadal), there are strongly correlated signals in physical and biological variables along the eastern boundaries of both gyres in the Northeast Pacific Ocean (NEP)—the currents of the Coastal Gulf of Alaska (CGOA) and the California Current System (CCS). Tide gauge and altimeter data suggest that the strengths of the boundary currents in these gyres covary out of phase on annual and interannual time scales (the equatorward CCS strengthens while the poleward and westward current in the CGOA weakens and vice versa [Chelton and Davis 1982]). Zooplankton volumes in the southern part of the CCS covary in phase with the interannual changes in the CCS transport, although the mechanisms responsible for the covariance are not clear (Chelton et al. 1982; Wickett 1967). On interdecadal time scales, there are data suggesting that zooplankton and salmon both covary out of phase in the two boundary currents (Roemmich and McGowan 1995; Brodeur and Ware 1992; Francis and Sibley 1991). Sardine in the CCS also covary in phase with salmon in the CGOA, but out of phase with salmon in the CCS (Kawasaki 1992). The interdecadal fluctuations of these populations, and others (Beamish, 1993), coincide with basin-scale physical changes in atmospheric forcing and surface ocean conditions (temperature, mixed-layer depth), although again the mechanisms responsible for the covariances are not known.

Program Goals

- To understand the effects of climate variability and climate change on the distribution, abundance and production of marine animals (including salmon and other commercially important living marine resources) in the eastern North Pacific.

- To embody this understanding in diagnostic and prognostic models, capable of elucidating ecosystem dynamics and responses on a range of time scales, including major climatic fluctuations.

A focus of the first goal is to better understand the mechanism(s) responsible for the covarying, but out of phase, production dynamics of zooplankton and fish of the CGOA and CCS ecosystems. The target fish species for U.S. GLOBEC studies in the NEP are salmon. Salmon were selected due to the economic impact of changes in salmon abundance and because their populations vary concident with climate variability (Francis and Hare 1994). Zooplankton are important as indicators of the productivity of the coastal ecosystem. Moreover, zooplankton are directly linked to salmon as their prey, and indirectly by being alternate prey for some salmon predators (e.g., pollock, hake, some birds). Thus, the **target species for process studies** in the coastal regions of both gyres are the **juvenile salmon** and the dominant crustacean zooplankton (**copepods and euphausiids**) upon which salmon and other predators in the ecosystem rely. While the process studies will focus on these species, other elements of the program (modeling, retrospective analysis, monitoring) can address other species that could elucidate NEP ecosystem changes in response to climate change.

Core Hypotheses

I. Production regimes in the Coastal Gulf of Alaska and California Current System covary, and are coupled through atmospheric and ocean forcing.

II. Spatial and temporal variability in mesoscale circulation constitutes the dominant physical forcing on zooplankton biomass, production, distribution, species interactions, and retention and loss in coastal regions.

III. Ocean survival of salmon is primarily determined by survival of the juveniles in coastal regions, and is affected by interannual and interdecadal changes in physical forcing and by changes in ecosystem food web dynamics.

Approach

U.S. GLOBEC will study the effects of past and present climate variability on the population ecology and population dynamics of marine biota and living marine resources, and use this information as a proxy for how the ecosystems of the eastern North Pacific may respond to future global climate change. **The program plans to use the strong temporal variability in the physical and biological signals to examine the biophysical mechanisms through which zooplankton and salmon populations respond to physical forcing and biological interactions in the coastal regions of the two gyres.** Annual and interannual variability will be studied directly through <u>monitoring</u> activities (over a 5-7 year period) and detailed <u>process studies</u> (over a 5 year period); variability at longer time scales will be examined through <u>retrospective analysis</u> of directly measured and proxy data. Coupled <u>bio-physical models</u> of the ecosystems of these regions will be developed and tested using the process studies and data collected from the monitoring programs, then further tested and improved by hindcasting selected retrospective data series.

Process studies in the NEP will focus on the causes of salmon mortality in the nearshore region during the first part of their ocean residence, and will include investigations of bottom-up (zooplankton production, salmon diet) and top-down interactions (predation by other fish, birds, and mammals). The **geographic locations for the studies** will include three types of environments: 1) the predominantly downwelling environment of the CGOA (surface convergence toward shore); 2) the moderate upwelling environment off Oregon/Washington (Region I of the CCS, characterized by surface divergence from shore with a nearly linear alongshore jet that may bar movement offshore but increase movement alongshore); and 3), the strongly upwelling environment off northern/central California (Region II of the CCS, characterized by surface divergence from shore with a complex meandering jet and eddy system that may transport organisms far offshore).

Monitoring and **retrospective** components of the Northeast Pacific U.S. GLOBEC program will make use of a **broader suite of species** than the process studies, especially focusing on species that might serve as indicators of ecosystem variability in the boundary currents. Examples of such indicators are the small pelagic fishes and nearshore benthic invertebrates. Population sizes of small pelagic fishes have been documented to covary interannually and interdecadally with changes in the physical environment. These relationships can be studied using fishery records and proxy estimates of abundance recorded in anoxic sediments. Thus, small pelagic fishes are prime candidates for inclusion in retrospective studies. Salmon ocean survival (a component important in determining year-class strength) is believed to be determined during their earliest marine phase in the nearshore region. This is also the region where mortality of benthic invertebrate planktonic larvae affects their rates of successful settlement back to suitable nearshore adult habitat. Thus, nearshore settlement of benthic invertebrates from the plankton, which can be monitored inexpensively at shore (intertidal) sites, could provide finely resolved estimates of spatial and temporal variability in nearshore conditions—including physical processes (transport, near-shore retention) and biological processes (growth)—important to salmon growth and survival. The details of the mechanisms causing variable growth and mortality of benthic invertebrate larvae, holozooplankton, and juvenile salmon need to be better understood in terms of nearshore transports, mixing dynamics, production and food-web relations. In addition to examining a broader suite of species, **monitoring and retrospective studies should also examine a wider range of geographic regions** in order to encompass basin-scale (retrospective and monitoring) and multi-decadal (retrospective) climatic processes.

Modeling is a central element of the U.S. GLOBEC NEP program and should also **encompass the broadest suite of species and geographic regions**. At the largest scales, models must capture the basin-scale interannual and interdecadal climate fluctuations, and should reproduce the differential biological responses (inverse phasing) of the salmon and zooplankton populations and production in the northern (CGOA) and southern (CCS) domains. Regional models of the boundary currents must include details of the coastal circulation and biophysical interactions, with connections to the basin-scale fluctuations. Models are also needed to predict salmon growth and survival during their early ocean phase, emphasizing the role of ocean conditions, productivity and predator abundances in determining the year class strength on interannual and longer time scales—i.e., to provide a foundation for the prediction of salmon recruitment and, ultimately, better management of sustainable salmon harvests under "non-steady state" ocean conditions.

Introduction

This implementation plan was developed by U.S. Global Ocean Ecosystem Dynamics (U.S. GLOBEC) to guide proposals intended to address how marine populations of the eastern Pacific, esp. the California Current and coastal Gulf of Alaska ecosystems, respond to climate variability and climate change. This document provides more specifics about the scientific research U.S. GLOBEC seeks to conduct in the eastern Pacific. It is based on earlier U.S. GLOBEC documents resulting from several community-wide meetings that provided forums where U.S. scientists from the oceanographic and fisheries communities could help specify the key scientific issues and develop U.S. GLOBEC research programs in the eastern Pacific. Following the initial large meetings for the California Current System (Sept. 1991 - Bodega Bay) and North Pacific (April 1995 - Seattle), many more additional scientific questions arose in both the North Pacific and California Current Ecosystems than U.S. GLOBEC could potentially investigate. Subsequent to each of the larger meetings, the program supported several smaller meetings, bringing key scientists together, to provide a clearer focus and priorities for a Northeast Pacific scientific program. Prior reports of the U.S. Global Ocean Ecosystem Dynamics (U.S. GLOBEC) research program describe the physical and biological oceanography, and list the central questions and goals for U.S. GLOBEC studies in these regions. For the California Current System, these are U.S. GLOBEC Report No. 7 (Report of the first California Current GLOBEC Workshop held at Bodega Bay in September 1991) and U.S. GLOBEC Report No. 11 (California Current Science Plan). For the coastal Gulf of Alaska, the relevant reports are U.S. GLOBEC Report No. 15 on Climate Change and Carrying Capacity of the North Pacific Ecosystem (U.S. GLOBEC, 1996a) and U.S. GLOBEC Report No. 16 titled Climate Change and Carrying Capacity (CCCC) Science Plan (U.S. GLOBEC, 1996b). Copies of these documents are available from the U.S. GLOBEC office (Phone: 510-643-0877; Fax: 510-643-1142; Email: kaygold@uclink4.berkeley.edu) at:

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The reports are also available on the world wide web from the U.S. GLOBEC homepage at **http://www.usglobec.berkeley.edu/usglobec/globec.homepage.html**.

Background

U.S. GLOBEC's research goal is to understand how climate variability and climate change impact marine populations and ecosystems sufficiently well to predict their responses to climate change in the future. We propose to accomplish this by developing a fundamental understanding of the mechanisms that determine how the abundance of key marine animal populations vary in time and space. We focus on the coupling between physical processes and animal population dynamics, particularly in planktonic populations. We assume that the physical environment is a major contributor to patterns of abundance and production of many marine animals because a majority of them (invertebrates and fish alike) spend at least a portion of their lives in the plankton. Since the zooplankton, including meroplankton and ichthyoplankton, are transported passively by ocean currents, they are susceptible to changes in ocean circulation and upper mixed layer dynamics. Zooplankton are also a key trophic link between phytoplankton and fish, so climate-driven variations in zooplankton abundance and production will affect ecosystem structure at higher trophic levels. Consequently, one approach to predicting and assessing the potential impact of climate variability on marine ecosystem dynamics is to focus on zooplankton and to seek to understand how the physical environment, both directly and indirectly, controls their population dynamics, and indirectly, controls the population dynamics of their predators.

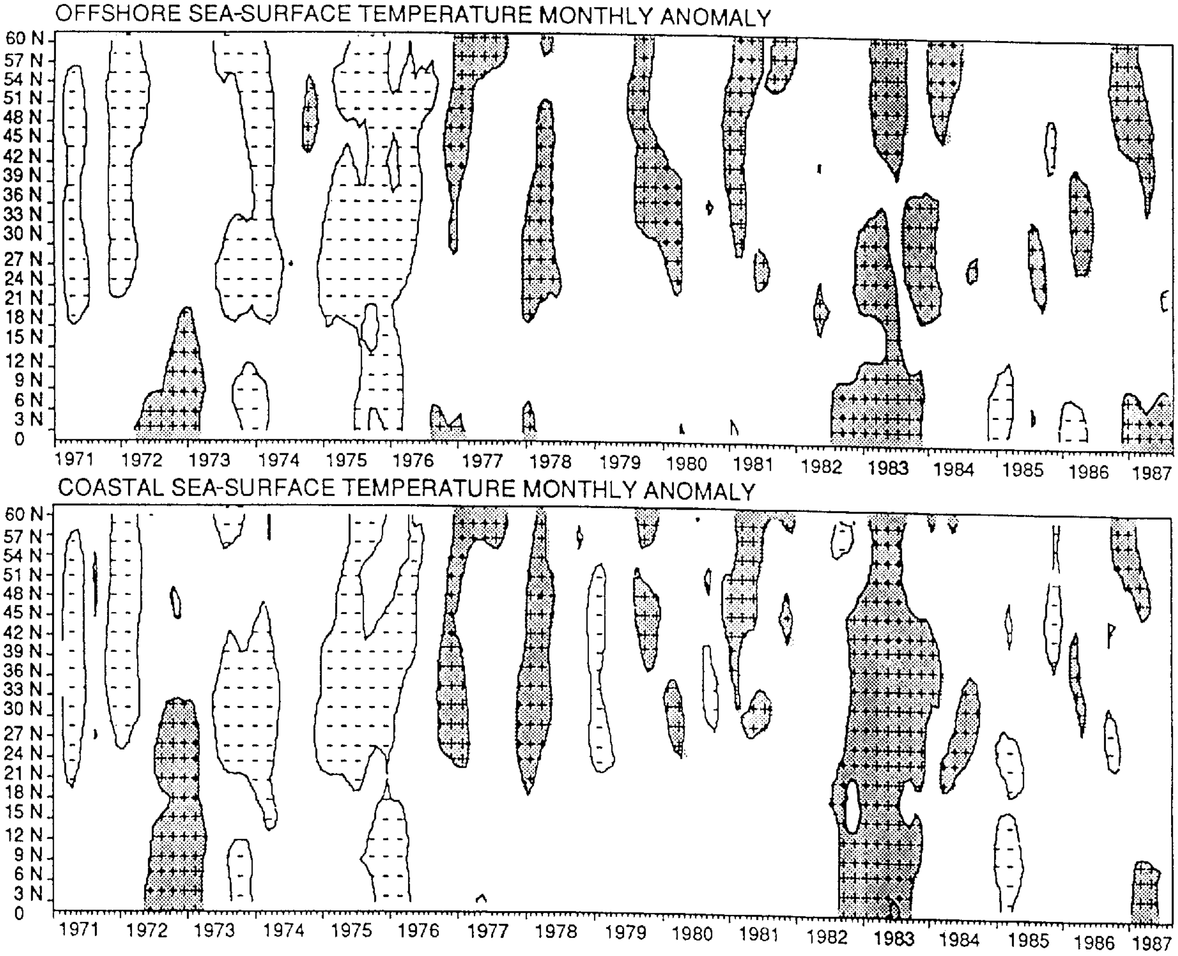
Physical processes, structures and characteristics in the ocean change as climate variability and forcing change. These modifications in physical patterns and processes will influence the distribution, abundances and dynamics of animal populations in the sea. U.S. GLOBEC will examine these biological responses to climatically–driven physical forcing in order to provide predictions of how existing natural climatic forcing and potential anthropogenic changes impact the marine ecosystem. U.S. GLOBEC is interested in a range of scales from the very small to the planetary. Examples of regional and global considerations might include (but are not limited to): 1) regional intercomparison of generic ecosystem types; 2) the basin scale linkages of regional ecosystems; and, 3) the dynamics of zoogeographic boundaries.

GLOBEC scientists study the coupling between physical and biological processes, using past and present climate variability as a proxy for future climate change. The research approach (and challenge) is to combine modeling, retrospective analysis of historical data, and process research into an integrated program that will produce regional climate change scenarios and quantitative assessments of the sensitivity of selected marine ecosystems to climate variability and climate change.

The Pacific Ecosystem

Recent studies (for references see U.S. GLOBEC Reports 11 and 15) have documented that the physical and biological dynamics of the eastern Pacific are sensitive to **natural climate variability** on time scales ranging from seasonal to interdecadal, and spatial scales from local to basin-wide. Ecosystem structure is known to be closely coupled to variations in physical forcing, thus sensitivity of the coupled physical-biological system to climate variability implies great sensitivity to **climate change**.

The physical structure, circulation dynamics and biology of the eastern North Pacific respond strongly to El Niño-Southern Oscillation (ENSO) and decadal time-scale regime (climate) forcings. As an example, Figure 1 shows sea surface temperature (SST) anomalies for coastal and offshore regions off the west coast of Central and North



OFFSHORE SEA-SURFACE TEMPERATURE MONTHLY ANOMALY

COASTAL SEA-SURFACE TEMPERATURE MONTHLY ANOMALY

Figure 1. Anomaly of monthly mean sea-surface temperatures from ships of opportunity (Cole and McLain, 1989). Contours are ±0.5°C, positive anomalies are shaded. "Coastal" (bottom panel) is approximately 0 to 200 km from shore; "offshore" (top panel) is approximately 200 to 600 km from shore.

America. This analysis shows both the influence of El Niño events (warm water at 0-30°N during 1972-73 and at all latitudes during 1982-83), and regime shifts (warm anomalies during winter and spring north of 24°N since 1976-77) on nearshore and offshore SST.

The strong connections between the eastern North Pacific and basin-wide oceanic and atmospheric circulations provide linkages to global scale climate changes, as shown by the well documented response of the California Current System to the basin-wide, interannual ENSO variability (see papers in Wooster and Fluharty, 1985; Chavez, 1996). The impact of ENSOs on marine populations is best documented for regions south of 35°N (Point Conception, CA) in the eastern North Pacific (see e.g., Barber and Chavez, 1986; McGowan, 1985; Smith, 1985; Fiedler et al. 1986). Weak El Niño events probably have little impact on marine populations north of the tropics in the eastern North Pacific, whereas some (but not all) strong El Niño events, like that of 1982-83, may impact populations from the equator to the subarctic (Miller et al. 1985; Pearcy et al. 1985).

The 1983 El Niño produced warm surface waters, weak upwelling and reduced offshore Ekman transport off the west coast of North America. For example, off Oregon, the plankton were affected by these conditions—a deep chlorophyll maximum persisted throughout the summer, zooplankton abundances were lower by a factor of three compared to usual summer abundances, and dominated by small, more southerly forms, and the distribution of fish larvae was atypical, with normally offshore larvae found inshore (Miller et al. 1985; Brodeur et al. 1985). The average size of coho salmon captured in the fishery in 1983 was the smallest on record, suggesting that low food availability led to poor growth (Pearcy 1992). The effects of the 1983 El Niño on the ichthyoplankton were apparently short-lived, with the distribution and abundance returning to normal patterns in 1984 and 1985 (Doyle, 1995).

The evidence cited above indicates that the 1983 El Niño had deleterious effects on the productivity of the pelagic environment off the Pacific Northwest, which negatively impacted commercial harvests of some fish stocks. It should be noted, however, that the biological impacts of El Niños can be positive or negative, and is often region and population specific. For instance, strong recruitment and good year classes of stocks of Pacific sardine and jack mackerel off California resulted from the 1958-59 El Niño, but Pacific Ocean perch, Dover sole and English sole off Oregon and Washington were negatively impacted by the 1958-59 El Niño (Bailey and Incze, 1985). The 1982-83 El Niño reduced the growth of northern anchovy juveniles and adults, but expanded the region in which spawning occurred (Fiedler et al. 1986). El Niño events can impact marine populations in a multitude of ways: 1) by altering food production, distribution, availability and phasing (timing) relative to the consumer populations; 2) altering transport regimes and residence times; 3) environmental warming that alters physiology or causes range shifts; and, 4) altering the intensity of predation pressure by introducing new or changed abundances of predators to a region (i.e., range expansions).

The climate of the subarctic North Pacific Ocean changed during the late 1970s (Fig. 2). The Aleutian Low intensified during winter (Trenberth and Hurrell 1994) and coastal sea surface temperatures rose rapidly by several degrees (Rogers and Ruggerone 1993; Royer 1989; Graham 1995). The deepening of the Aleutian Low resulted in more vigorous cyclonic circulation of the North Pacific subarctic gyre, and a deepening of the mixed layer in the North Pacific subtropical anticyclonic gyre. A dramatic shift in ocean climate also occurred in the California Current System. The warm phase/cool phase shifts in the California Current appear to be linked to the intensity of the Aleutian Low (Trenberth 1990; Graham 1994; Miller et al. 1994b; Trenberth and Hurrell 1994). An

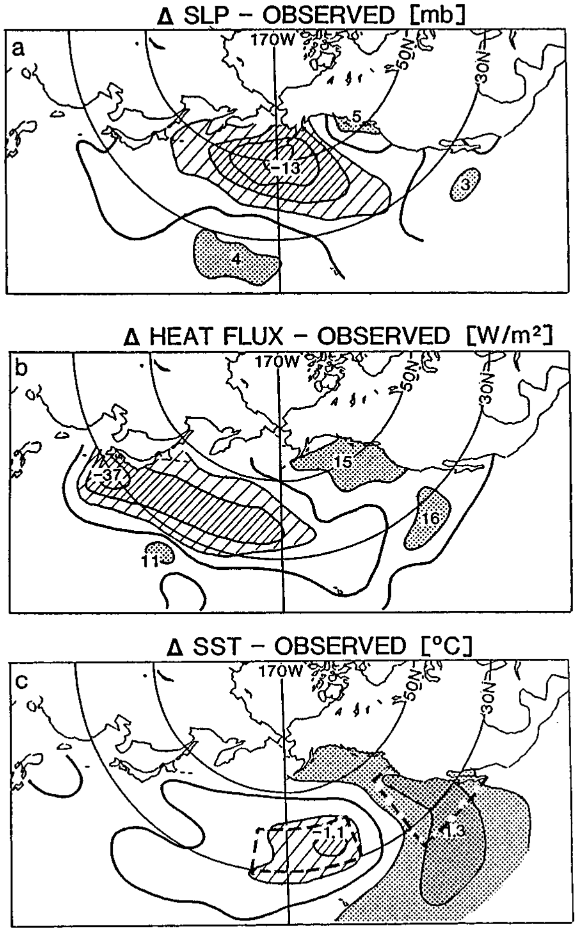


Figure 2. Difference fields for winter conditions for the period 1976-77 through 1981-82 minus the period 1970-71 through 1975-76. Winter defined as Dec-Feb. a) COADS sea-level pressure, b) COADS surface heat flux, c) COADS sea-surface temperature. (from Miller et al., 1994a).

earlier shift from the warm phase to the cool phase occurred in the mid-1940s (Miller et al. 1994a). The shift in 1976-77 is particularly well documented because data on atmospheric, sea surface and subsurface ocean conditions were sufficient to demonstrate the basin scale nature of the shift.

Large scale (longer-term) shifts in atmospheric pressure patterns and intensities may impact El Niño dynamics occuring at shorter time scales. Wang (1995) describes different warming patterns of the Pacific Ocean during onset of El Niños before 1977 (1957, 1965, 1972—warming of coastal water off South America preceeded central Pacific warming by ca. 9 mos.) and El Niño's after 1977 (1982, 1986-87, 1991-95—the central Pacific warmed before the coastal waters off Ecuador).

Using vertical temperature profile data, Polovina and coauthors (Polovina et al. 1994; 1995) document the changes in North Pacific winter and spring mixed layer depth (MLD) and mixed layer temperatures (MLT) of the North Pacific. MLD in the subtropical and transition zones of the North Pacific were 30-80% deeper during 1977-88 than during 1960-76. Across the subarctic zone, including the Gulf of Alaska, MLD was 10-30% shallower during the later period than during the earlier. MLT in the subtropical gyres was 0.5-1.0°C colder after 1977 than earlier, while in both the Gulf of Alaska and along the entire Pacific coast of North America, MLT after 1977 was 0.5-1.0°C higher than it was in 1960-67. Using a plankton production model, Polovina et al. (1995) argue that the changes in winter and spring MLD and MLT could have resulted in 50% higher primary and secondary production in both the subarctic and subtropical realms of the North Pacific. They conclude that decadal time-scale and basin spatial-scale changes in MLD and MLT in the North Pacific are related to the intensification of the Aleutian Low Pressure System, and provide a mechanistic link between atmospheric circulation variability and oceanic ecosystem productivity. Productivity of higher trophic levels (lobsters, birds, seals) off Hawaii appears to respond also to the change in ocean climate of the late 1970's (Polovina et al. 1994).

Biological responses to interdecadal basin (or global) scale variability have been recognized in both the California Current System (CCS) and the Coastal Gulf of Alaska (CGOA). Perhaps the best documented are in the abundance (or distribution) of fish populations, like the salmonids (see collection of papers in Beamish 1995 and Beamish and McFarlane, 1989; Beamish 1993; Bailey et al. 1995; Hare and Francis 1995; Francis and Hare 1994; Brodeur and Ware, 1995) and small pelagic fish (sardines and anchovies) (Lluch et al. 1989; Kawasaki 1992). One cannot help but be impressed by the remarkably similar patterns in abundance (as indicated by catch) of Pacific salmon from the subarctic Pacific, and sardines from the California, Peru/Chile and Japanese fisheries over the past century (Fig. 3). Periods of high and low catches of these stocks are related to northern hemisphere temperatures, with highest catches occuring during warm periods and vice versa (Klyashtorin and Smirnov, 1995). For the fisheries in Figure 3 for which records exist to the early 1900s, catches increased during the early part of the century, until about the mid to late 1930's. During the 1940s, each stock began to decline with lowest abundances in the late 1960s-early 1970s. Salmon catches rebounded sharply in the late 1970s and 1980s (Pearcy 1992). The commercial salmon harvest in Alaska in the 1980s exceeded that of the 1930s peak; however, some of this recent resurgence is due to salmon ranching (returns of hatchery released fish).

The catch records of sardines from the Pacific mirror that of the Alaskan salmon harvest. Historical maximum catches of California and Japanese sardines in the 1930s-early 1940's were followed by a rapid, precipitous decline during the succeeding three decades. Since the late 1970s, sardines in Peru/Chile and Japan have rebounded strongly;

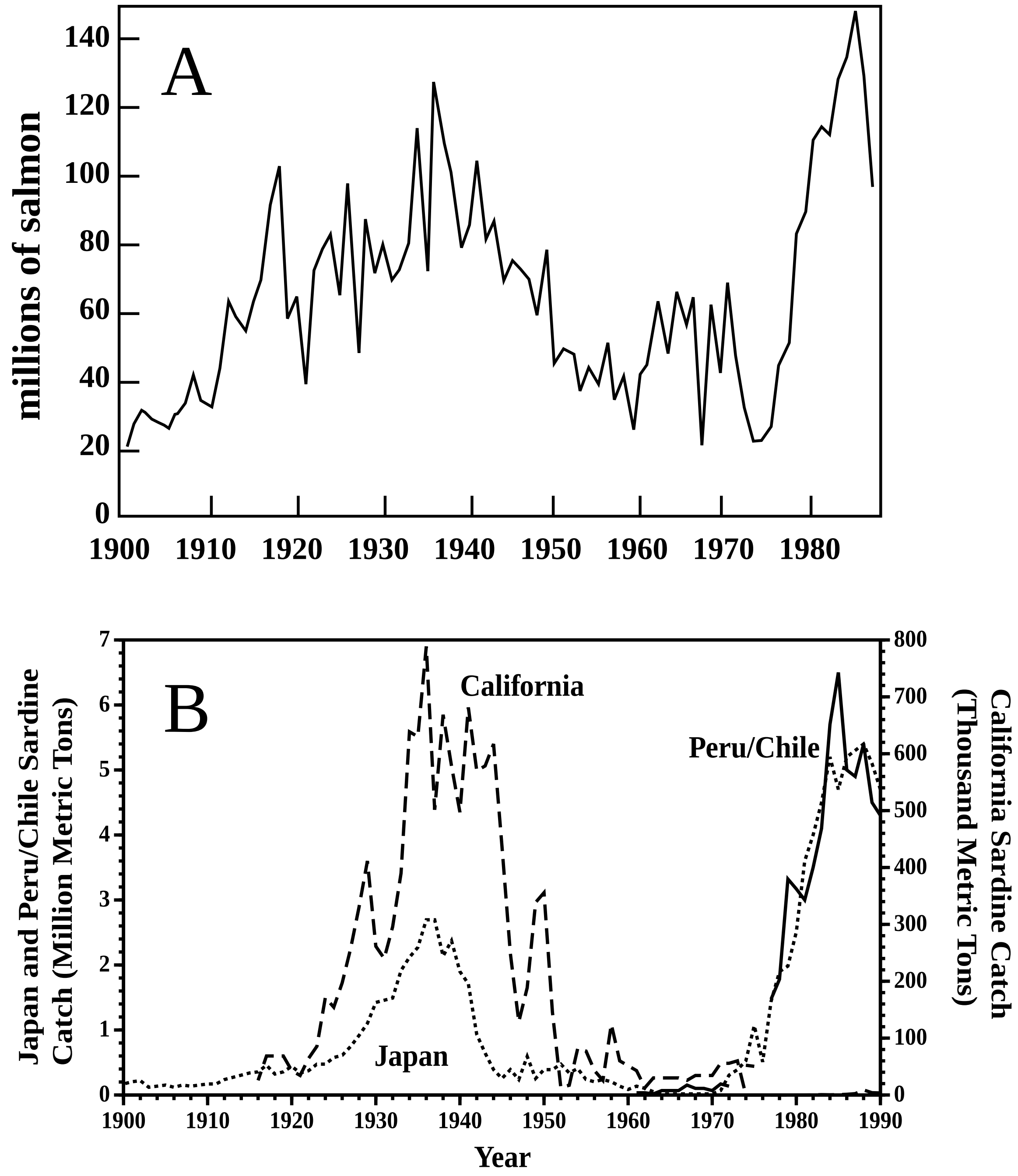


Figure 3. A) Commercial salmon harvest of Alaska, 1900-1988. Data are from the Alaska Department of Fish and Game. (Redrafted from Pearcy, 1992). B) Historical catches in the sardine fishery of Japan (dotted line), California (dashed line), and Peru-Chile (solid line). (Modified from Kawasaki, 1992). Note different ordinate scales.

in fact the maximum catch of Japanese sardines during this latter period exceeded by a factor of two the maximum catches from the 1930s. Commercial fisheries off Peru and Chile began only in 1960, when a fishery developed on the abundant anchoveta; sardines at that time were relatively rare, but increased in abundance during the 1970s and 1980s. Unlike the case of the North Pacific salmon, there have been no remedial efforts (hatcheries, habitat modification, etc.) involved in the sardine's recovery in these ecosystems. California sardines have been increasing in abundance (with high population growth rate) since the late 1970s (Barnes et al. 1992), but the reestablishment of large stocks after the ocean conditions changed has been slow because the stock was so depleted during the 1960s.

The dramatic fluctuations in catches described above are likely due in part to changing patterns of fishing effort and the consequences of overexploitation. Nonetheless, the concordance among species suggests the effects of an overriding climate influence.

Long term, interdecadal scale variations in zooplankton biomass in the Southern California Bight (SCB) of the CCS are documented by Roemmich and McGowan (1994) using the CalCOFI data set. Zooplankton biomass in the SCB began a ca. 5-fold decline at approximately the time of the mid-1970's warming event in the CCS (Fig. 4). Elsewhere, zooplankton biomass in the subarctic Pacific during the 1980s is ca. double that of 1956-1962 (Fig. 5), and the peak biomasses in the recent period are more coastally distributed than in the earlier period (Brodeur and Ware 1992; Brodeur et al., in press). These results suggest major shifts in the productivity of the subarctic gyre (increased) and the southern part of the California Current (decreased) during the present warm regime (warm marginal currents post 1976). We note that changes in the zooplankton populations in the northern part of the California Current during this period are not known because there was no systematic sampling (like CalCOFI) in this region.

To address questions about the physical and biological impacts of climate change requires data spanning long time horizons--from the past, present and future. Each of these is a component of U.S. GLOBEC studies: variability and change in the past is examined through **Retrospective Data Analysis**; conditions and biophysical interactions at present are examined through **Process-Oriented Field Studies**; and, documenting future variability and change is the rationale for instituting frequent, sustained **Monitoring** of the environment. **Modeling** and **Synthesis** activities will integrate the results from U.S. GLOBEC's studies, and from the research, monitoring, and retrospective activities, so that the consequences of climate change on the coastal marine ecosystem can be evaluated and projected.

U.S. GLOBEC research in the Northeast Pacific will focus on the boundary currents—the equatorward flowing California Current along the southern region, the poleward and westward flowing Alaskan Current and Alaska Coastal Current in the north, and the interior west wind drift which diverges at the coast of North America and contributes to both boundary currents (Fig. 6). Retrospective studies can utilize a rich history of time-series including research surveys of zooplankton and fish, commercial fisheries data, environmental data, and paleo records from sediments. These data sources can be used to define better the relation between large-scale climatic shifts, changes in population distributions and abundances, regional-scale transports, and local-scale processes, such as predation, upwelling/downwelling, mixed-layer depth, and zooplankton and fish production. Monitoring transects should be (re)established to provide ongoing time series of key processes at several locations off northern/central

This figure could not be included in this document because AAAS refuses to permit electronic (e.g., on the web) distribution of copyrighted figures. The figure that should be here is Figure 2, panel A from Roemmich, D. and J. McGowan. 1995. Climatic warming and the decline of zooplankton in the California Current. Science, 267, 1324-1326.

Figure 4. Time series (1950 to 1994) of zooplankton volumes (cm^3 per 1000 m^3 water sampled) from stations along CalCOFI transect line 90. Line 90 extends onshore-offshore within the center of the California Bight. (Reprinted with permission from Roemmich and McGowan, 1995. Copyright 1995 American Association for the Advancement of Science).

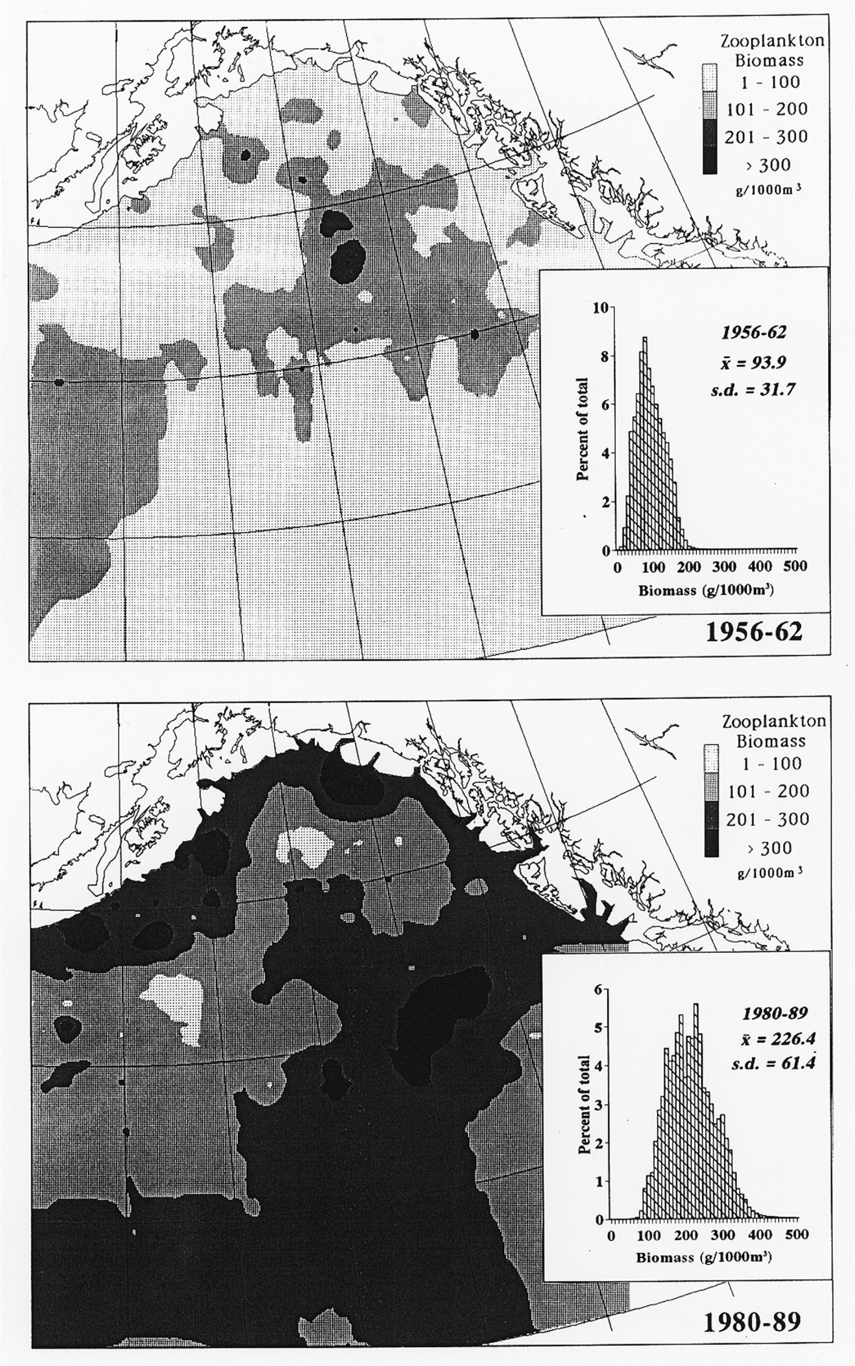


Figure 5. Summer biomass distributions of zooplankton collected in 1956-1962 (top) and 1980-1989 (bottom) in the North Pacific. The distributions are composites of sampling from June 15 to July 30 and over the years indicated. (from Brodeur et al, in press, reproduced with permission)

California, Oregon/Washington, and in the CGOA—preferably at locations with good historical records.

U.S. GLOBEC's Northeast Pacific process studies will investigate the way in which zooplankton and juvenile salmon are affected by mesoscale circulation in the coastal ocean. Mesoscale dynamics are a focus in the CCS and CGOA because they dominate much of the physical and biological dynamics (e.g., see satellite images), and because they differ regionally as a result of differences in wind stress, intensity of coastal upwelling/downwelling, coastal morphology, freshwater inflow, and the influence of advection, turbulence and buoyancy. Since climate-mediated changes in large scale atmospheric and oceanic forcing have substantial impact on mesoscale dynamics, a field research effort focused on this spatial scale is warranted. In addition to these physical differences along the west coast, there are regional differences in planktonic, benthic and fish assemblages, overall productivity, and the timing of production cycles. The northern domain—approximately from the Queen Charlotte Islands, BC to the Aleutian archipelago—of the Pacific coast is strongly influenced by coastal freshwater input, which results in an intense baroclinic, buoyancy-driven current along the coast, with eddies induced by the shear and topographic influences (Fig 6). Nursery areas and migration routes of both juvenile and adult fish parallel the resulting frontal boundary; the coastal current may be both a "conduit" for alongshore transport and migration and a "barrier" to cross-shelf motion (Thomson et al. 1989). The coastal Gulf of Alaska is a predominantly downwelling system. Conversely, southern British Columbia, Washington, Oregon, and northern and central California are predominantly upwelling systems. As described in earlier GLOBEC reports No. 7 (1991) and No. 11 (1994), Washington and Oregon north of Cape Blanco are characterized by winds that reverse seasonally, moderately strong upwelling (occuring in summer only), a linear coastline with few large promontories, predominantly alongshore advection, and few mesoscale features (e.g., eddies, filaments, offshore extending squirts, jets). This contrasts with the situation in northern and central California (to Pt. Conception in the south), where winds remain mostly upwelling favorable throughout the year, strongest in spring and summer, there are major promontories jutting into the ocean, offshore advection is large, and complex mesoscale features (squirts, jets and eddies) are prevalent (Fig. 7). These regional differences (see summary in Fig. 8) in physical-biological linkages and the physical forcings provide a natural laboratory for comparing potential changes in marine populations due to climate variability and climate change over the larger, basin-scale.

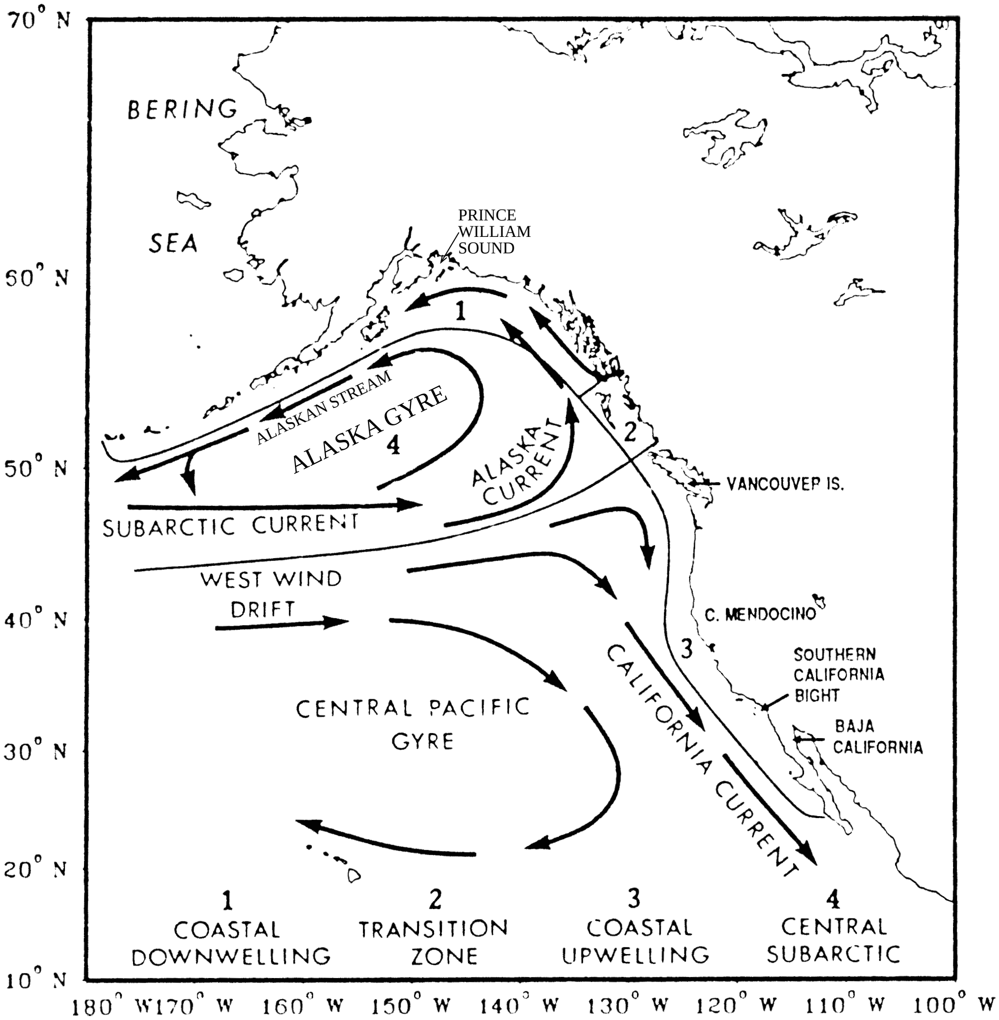


Figure 6. Fisheries production domains and general circulation in the Northeast Pacific Ocean (from Ware and McFarlane, 1989). Regions 1-4 are named at the bottom of the figure.

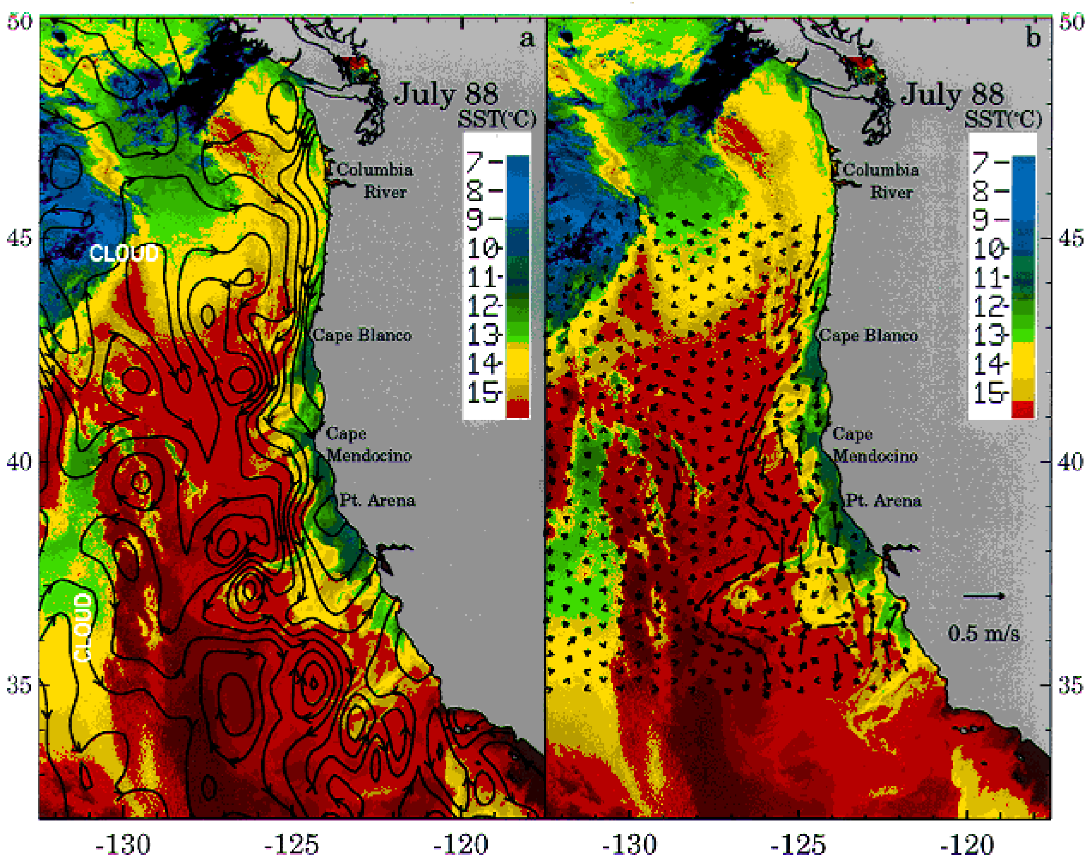


Figure 7. Summer (1988) circulation of the California Current. a) Geosat height from a single cycle in July 1988, contoured and overlaid on a coincident SST field; b) estimated surface velocity from automated feature tracking using five pairs of SST images over a 36 hour period, overlaid on SST. (from Strub and James, 1995)

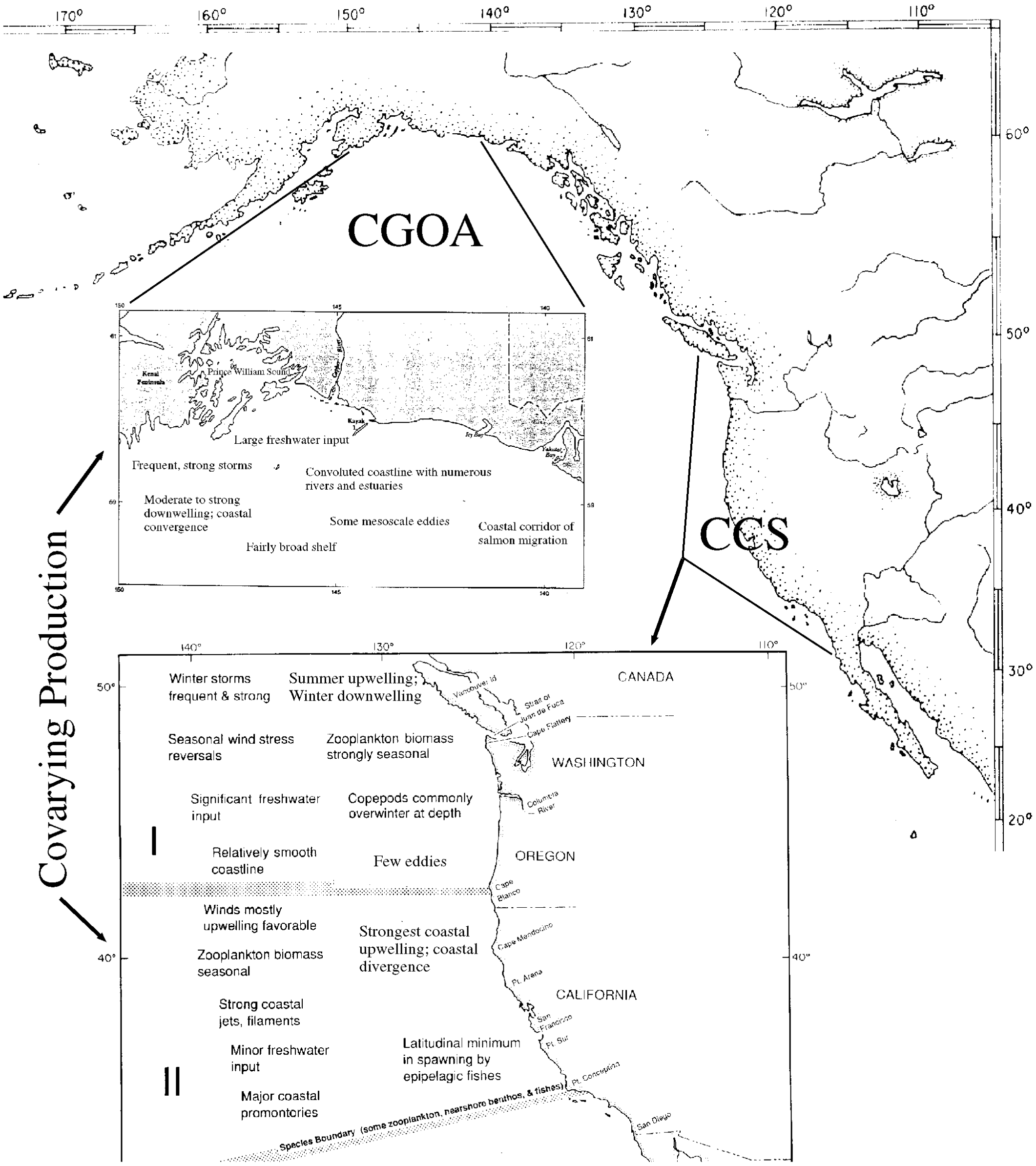


Figure 8. Generalized regional variations in physical and biological processes and characteristics within the boundary currents in the eastern North Pacific.

Goal, Approach and Core Hypotheses

OVERALL GOAL: To understand the effects of climate variability and climate change on the distribution, abundance and production of marine animals (including commercially important living marine resources) in the eastern North Pacific. To embody this understanding in diagnostic and prognostic ecosystem models, capable of capturing the ecosystem response to major climatic fluctuations.

OVERALL APPROACH: To study the effects of past and present climate variability on the population ecology and population dynamics of marine biota and living marine resources, and to use this information as a proxy for how the ecosystems of the eastern North Pacific may respond to future global climate change.

Hypothesis I.	Production regimes in the Coastal Gulf of Alaska and California Current System covary, and are coupled through atmospheric and ocean forcing.
Hypothesis II.	Spatial and temporal variability in mesoscale circulation constitutes the dominant physical forcing on zooplankton biomass, production, distribution, species interactions, and retention and loss in coastal regions.
Hypothesis III.	Ocean survival of salmon is primarily determined by survival of the juveniles in coastal regions, and is affected by interannual and interdecadal changes in physical forcing and by changes in ecosystem food web dynamics.

Regional Priorities and Site Selection

U.S. GLOBEC's Initial Science Plan (U.S. GLOBEC 1991b) identified a number of criteria that should be considered in the selection of sites for U.S. GLOBEC field studies. Those scientific and strategic criteria are:

Climate Change Context—the research program should have the capability to link its results to climate change. As discussed above, the ecosystems of both the CCS and CGOA regions have responded directly and strongly to interannual and interdecadal variability in climate forcing.

Target Species in Holozooplankton, Fish and Benthos—Both the CCS and CGOA have numerous species, some of them economically important, within each category that are potentially impacted by climate variability and climate change (see the section below on target species selection).

Population Dynamics as the Output—The research should, to the extent possible, be designed so that target populations are demographically and geographically distinct. U.S. GLOBEC seeks to understand how *populations* fluctuate in response to physical processes. This is probably the most difficult criterion to satisfy in the CGOA and CCS ecosystems, and will require different approaches than those used to study the populations residing on Georges Bank.

Focus on Processes and Mechanisms—GLOBEC aims to understand the mechanisms responsible for population and ecosystem responses. This is required in order to use the results of the field research programs in the development of models capable of predicting population and ecosystem responses to conditions that in the future differ from the present. The studies outlined below for the CGOA and CCS focus on physical processes and their impact on the populations such as: onshore-offshore transport; physical impacts on the match-mismatch of resources and consumers, etc. (see sections below, and also page 5).

Historical Database—Study sites should have considerable data on the distribution and abundance of target species, on the physical oceanography, and on climate. The CCS and CGOA ecosystems that are the selected sites have been studied extensively, as is indicated by some of the relationships discussed earlier relating climate, physics and population abundances.

Modeling Input—Previous modeling of the ocean's circulation and ecosystems are important, as is the modeling that will be supported directly by the U.S. GLOBEC program during the field period. Predictive models are one of the types of anticipated products of all U.S. GLOBEC regional programs. Physical circulation models have been developed for the basin as a whole and for some regions of the CCS and of the CGOA. Biological models are less developed and will be a specific focus of the U.S. GLOBEC program, as will coupling between basin-scale and regional models.

New Technology—U.S. GLOBEC regional study programs should utilize recently developed technologies that offer improved data sets; these improvements could be better temporal or spatial resolution, or techniques for measuring rates (such as growth, etc.) in new ways.

International Collaboration—U.S. GLOBEC studies of the CCS and CGOA will be the U.S. contribution to a larger international effort. First, modeling, monitoring and retrospective analysis of this U.S. GLOBEC initiative will extend to Pacific regions not specifically the focus of U.S. GLOBEC process studies, and will provide linkages to other programs (see the sections on modeling, monitoring and retrospective analysis in the implementation plan below). Specifically, in the North Pacific the PICES (North Pacific Marine Science Organization) program, in conjunction with GLOBEC International, hopes to coordinate multiple regional experiments investigating both small pelagic fish stocks and Pacific salmonids. Canada GLOBEC is supporting investigations focused on inner shelf zooplankton populations and salmon. Those studies include both modeling and process investigations of the relations among primary production, zooplankton distribution and abundance, shelf circulations, and salmon distribution and growth. One of the initiatives being developed by the IAI (Inter-American Institute for Climate Change) program is a comparative study of the upwelling ecosystems of the North and South Pacific west coasts. U.S. GLOBEC's studies proposed here for the California Current ecosystem are a possible model for the development by IAI of similar research activities off Chile and Peru. Although the specific focus of the science supported by IAI on the west coast of the America's is not yet known, hopefully, those studies will complement U.S. GLOBEC's research on zooplankton and salmon in the Northeast Pacific Moreover, research conducted off of North America under the auspices of the GLOBEC International Small Pelagics and Climate Change (SPACC) program will focus on the Southern California Bight and Northern Mexico, providing a southward extension to the studies supported by U.S. GLOBEC further north.

Generality of System, both Physical and Biological—This criterion is critical if U.S. GLOBEC's results are to be applicable to regions other than those specifically targeted for field investigation. The CGOA and CCS systems provide a natural comparison of downwelling and upwelling ecosystems, respectively. Other ecosystems, occupied by similar species, and with similar physical processes, occur across the globe. Understanding gained by studying these specific ecosystems will lead to a broader understanding of those other similar ecosystems elsewhere.

The planning process for U.S. GLOBEC Northeast Pacific studies has included broad participation of oceanographic and fisheries scientists from the U.S. and other countries. Planning for ecosystem studies in the Pacific by U.S. GLOBEC spanned the region from the Bering Sea to the Southern California Bight. However, it is not possible to study the entire region with the funding available (or anticipated). **Thus, for process-oriented field studies in the Northeast Pacific, the Scientific Steering Committee (SSC) of the U.S. GLOBEC program has selected two domains as their highest priority: (1) the northern half of the California Current System (CCS); and (2) the Coastal Gulf of Alaska (CGOA). Two contrasting subregions within the CCS will be studied: the area between Vancouver Island, Canada and Cape Blanco, Oregon (Region I of the CCS) and the area between Cape Blanco, Oregon and Point Conception, California (Region II of the CCS).** As reviewed above, ecosystems in these regions show clear, qualitative and quantitative state changes in the physics, productivity, zooplankton and fish in recent years, presumably in response to changes in large-scale physical forcing of the North Pacific. **On this larger scale, retrospective studies, modeling and monitoring activities will be less limited** and are expected to include the important basin-scale processes and fluctuations, with higher resolution in the priority areas. **U.S. GLOBEC desires to better document the changes in these regions, their connections to the basin-scale climatic variability, and the mechanisms by which the changes occurred. An ultimate goal is to develop diagnostic and prognostic models using our improved understanding of these mechanisms.**

Anticipated Products

A successful U.S. GLOBEC program in the Northeast Pacific will produce four benefits that would not occur without this program.

- **Improved knowledge of the impact of climate variability on marine ecosystems** of the eastern North Pacific. Specifically, the program will elucidate mechanisms controlling the abundance and distributions of marine populations, including commercially important fish and benthic species. The improved mechanistic understanding of the coupling between physics and biology will be helpful no matter how future climate evolves. When coupled with improved monitoring systems and biophysical models, the improved mechanistic understanding will improve the reliability of predictions of the future composition of marine communities.

- The development and/or refinement of **coupled biophysical models** that could be used to examine hypotheses regarding potential impacts of climate variability on marine ecosystems. These models will improve our ability to integrate biological, physical, and climatological observations in coastal ecosystems.

- Data sets will be collected and analyzed during the program that will provide the **basis of future research** activities in the region. These include historical data sets, data from process-oriented field studies, and data from any longer-term monitoring that we initiate.

- **A new basis for resource management.** The information generated by this U.S. GLOBEC program will enable those responsible for managing living marine resources to move beyond the traditional fisheries management approach towards a new paradigm that integrates environmental and ecosystem data to better account for variability in production and recruitment. It is now recognized that variability in ocean physical conditions and plankton communities impact the production of living marine resources. It is essential that the environment and ecosystem become a part of fisheries management and that a more holistic, multispecies, ecosystem-oriented approach be used to monitor and regulate the health of our nation's coastal ecosystems, including it's valuable commercially harvested species.

Program Implementation

Introduction

An overall objective of U.S. GLOBEC's Northeast Pacific program is a comparison of the impacts of climate variability and change on the marine populations of the CCS and the CGOA. As documented above, physical and biological variables in these two boundary currents appear to covary, although their basic physical dynamics are quite different. The coastal currents in the CGOA are driven by downwelling-favorable winds, which produce Ekman transports at the surface that converge toward the coast. This convergence interacts with the large freshwater runoff to produce a buoyancy-driven poleward current, which remains intensified next to the coast due to the wind-driven coastal surface convergence. This flow is strongest in winter and is weak or absent only for a brief period in summer. Given this downwelling nature, the mechanism by which nutrients reach the surface is unknown. Moreover, transport of offshore zooplankton to the coast and retention of zooplankton and juvenile salmon near the coast in this region appears to be favored by the coastally convergent surface flow.

Similar downwelling-favorable, coastally convergent conditions occur off Oregon, Washington and northern California in fall and winter (with a much weaker fresh water input), causing the poleward Davidson Current. In this region, however, equatorward winds in spring and summer create moderate to intense upwelling, with divergence of the surface currents away from the coast (increasing in strength from north to south). Thus the flow works against retention of zooplankton and juvenile salmon near the coast, while it enhances nutrient enrichment. Retention near the coast may be accomplished by the alongshore jet that develops off Oregon and Washington (serving as a barrier), by the intense mesoscale eddy field that develops off California (populations remaining in eddies until fall and winter winds transport them back onshore), and by animals taking advantage of subsurface onshore upwelling flow.

Interannual and interdecadal changes in the strength and position of the major North Pacific atmospheric pressure systems (the Aleutian Low and the North Pacific High) apear to force these two boundary currents to covary out of phase, possibly changing the amount of transport into each system from the central North Pacific (in the West Wind Drift). The strength of the boundary current transports, coastal convergence/divergence and mesoscale activity within each system also change in response to atmospheric forcing, as do the surface temperature and mixed-layer depth. Changes in these physical variables appear to cause changes in the zooplankton (Fig. 4 & 5) and fish (Fig. 3 & 9) populations, and may move the boundaries between biogeographical provinces.

This phasing of the ocean environment and marine populations to common atmospheric forcing argues for concurrent studies of these regions (CGOA and CCS). Given these strong signals at interannual-to-interdecadal time scales, U.S. GLOBEC plans to use a 5-7 year program of observations (monitoring and process studies) to 1) document changes in the physics and biology of these regions, and 2) examine the mechanisms by which the changes in the physical conditions alter zooplankton and salmon populations in these two boundary currents. Retrospective analysis of longer historical data sets will address changes that might have occurred in a broader suite of species. Ecosystem modeling, linking the basin-scale to regional-scale physical processes with population and food web dynamics, will attempt to reproduce the observed variability at all time scales.

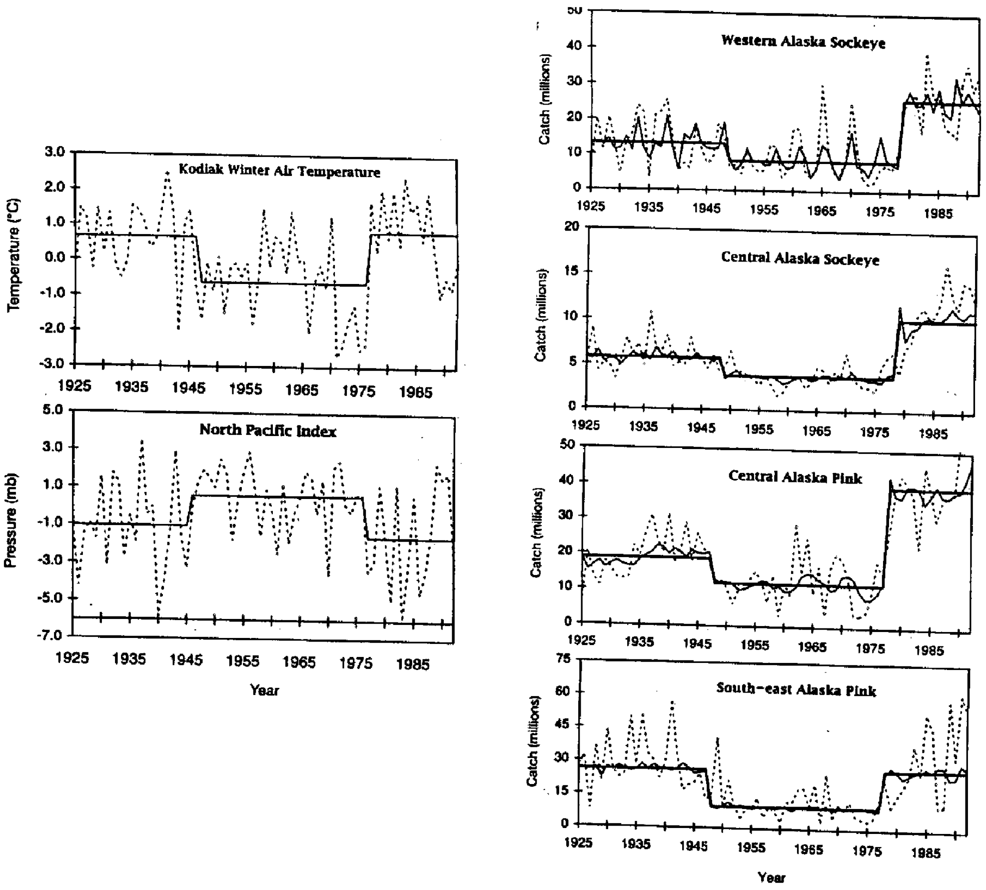


Figure 9. Results of intervention analysis showing environmental shifts (Kodiak Winter Air Temperature and North Pacific Index) and the shifts in catch of sockeye and pink salmon from the North Pacific. (from Francis and Hare, 1994)

Program Time-Line

U.S. GLOBEC proposes to conduct alternate-year process studies of theCCS and CGOA ecosystems, concurrent with longer-term monitoring of both systems for a 5-7 year period. We expect that modeling, retrospective data analysis, and monitoring, will begin prior to the 5-7 years of process-oriented studies, and that final synthesis will extend beyond the conclusion of the field studies. Synthesis in this timeline includes coordination and integration activities that link together various research, monitoring, and modeling activities occuring in the Northeast Pacific (see section on Synthesis; p. 53). Using five years of process studies as an example, we envision the following time-line (Table 1) for Northeast Pacific U.S. GLOBEC activities.

Table 1. Time-line for U.S. GLOBEC Northeast Pacific Program.

Activity	Yr 1	Yr 2	Yr 3	Yr 4	Yr 5	Yr 6	Yr 7	Yr 8
Modeling	XXX	XXX	XXX	XXX	XXX	XXX	XXX	
Retrospective Data	XXX	XXX	XXX	XX	X			
Synthesis	X	X	XX	XX	XX	XXX	XXX	XXX
CCS								
Monitoring	X	XX	XXX	XXX	XXX	XXX	XXX	
Process			XXX		XXX		XXX	
CGOA								
Monitoring	X	XX	XXX	XXX	XXX	XXX	XXX	
Process				XXX		XXX		

This timeline reflects several trade-offs that will be necessary to accomplish an integrated Northeast Pacific (NEP) GLOBEC program. First, there are insufficient ship resources to conduct process studies in the CCS and CGOA simultaneously. Process studies will be conducted during years 3-7 of this timeline—the emphasis in years 3, 5, and 7 is on the CCS; in years 4 and 6, the CGOA will be the primary focus. Modeling, retrospective data analysis, synthesis and monitoring will overlap in time. Monitoring activities will begin prior to the process studies, but will ramp up to a full effort over three years, as experience suggests which observations are crucial and the frequency of monitoring required. The second limitation is that to accomplish the program above will require that the monitoring activities be restricted. Frequent, broad-scale, detailed spatial surveys, of the type being conducted by U.S. GLOBEC on Georges Bank, are unaffordable on the spatial scale of the program proposed for the Northeast Pacific. Monitoring work in the NEP program will consist of standard suites of observations obtained periodically along several key onshore-offshore transect lines. These dedicated surveys will be supplemented by buoy, satellite, and volunteer observing ship data. See the section below on monitoring. An important aspect of U.S. GLOBEC research in the Northeast Pacific is a synthesis of (1) existing data resources from the CCS and CGOA, (2) data generated by new monitoring programs, (3) U.S. GLOBEC supported process studies in the CCS and CGOA, and (4) data collected by other programs (CalCOFI, SPACC, IAI-Amigo, SEA, EVOS, OCC, PNCERS, CLIVAR/GOALS, etc.) studying the ecosystems of the California Current, Coastal Gulf of Alaska, and the entire Pacific Basin (see the section below on Synthesis).

Target Species and other Species of Interest

As described in earlier reports, U.S. GLOBEC has developed a number of criteria as guidelines for the selection of key (or target) species for study. Very few species or assemblages can satisfy all of the criteria (Table 2), but the species selected below come very close. Table 3 lists the species whose life histories and vital rates will be determined during U.S. GLOBEC investigations. For the marine holoplankton, this will encompass their entire life-span; for the salmon, the earliest marine phase, as juveniles in the coastal ocean, when ocean survival is probably established, is of greatest interest.

Table 2. Criteria for selecting target species in U.S. GLOBEC Northeast Pacific studies. (Modified from a table presented in U.S. GLOBEC Report 11. (U.S. GLOBEC, 1994))

- Likely to be impacted by hypothetical climate change scenarios

- Economically or ecologically important, either as a dominant member of the ecosystem, or through interactions with other species

- Has larval planktonic stage or is holoplanktonic

- Evidence that life history variability is linked to environmental variability

- Widely distributed species, or having life-histories and/or ecological interactions representative of many other species, thus providing opportunities for large-scale spatial comparisons

- Demonstrated evidence of long-term shifts in abundance

- Distribution associated with physical features and/or faunal boundaries

- Analogous species occur in other ecosystems

- Has existing long-term record of abundance (and maybe distribution and growth)

U.S. GLOBEC studies in the CCS and CGOA will focus on growth, recruitment and mortality of the resident and transient marine populations, and how these measures of "population success" are controlled by climate-modulated changes in the physical environment. Because of the large latitudinal separation of the CCS and CGOA, comparative studies of the same species in the two regions are difficult (see below). **The process studies proposed below target marine zooplankton (esp. copepods of the genera *Calanus* and *Neocalanus* and euphausiids of the genera *Euphausia* and *Thysanoessa*), and the juvenile stage of several salmonids—pink salmon in the CGOA, and coho and chinook salmon in the CCS (Table 3).**

Although juvenile salmon do not have a planktonic larval stage, they are selected as target species because they satisfy all of the other U.S. GLOBEC criteria, and because during the presumed "critical" period of its ocean life history, alongshore (and perhaps offshore) advection may overpower their swimming ability. Moreover, salmon have shown responses in growth or survival to interdecadal or shorter period (e.g., El Niño's impact upon Oregon coho) alterations of the ocean environment. For example, salmon catches from the North Pacific increased sharply in the late 1970's, especially in Alaska (Pearcy 1992; Beamish and Bouillon 1993; Francis and Hare 1994; see Fig. 9). During this recent period of high production, the sizes of maturing salmon in some North

American and Asian populations were diminishing (Kaeriyama 1989; Ishida et al. 1993); however, the role of climate variation in this trend is unclear.

Table 3. Target species for U.S. GLOBEC **process studies** in the Northeast Pacific.

CCS—Region II Central California	**CCS—Region I Oregon**	**CGOA—Prince William Sound Region**
Holoplankton:	Holoplankton:	Holoplankton:
Calanus spp.	*Calanus* spp.	*Calanus* spp.
Euphausia pacifica	*Euphausia pacifica*	*Euphausia pacifica*
Thysanoessa spinifera	*Thysanoessa spinifera*	*Thysanoessa spinifera*
		Neocalanus spp.
Juvenile Salmonids:	Juvenile Salmonids:	Juvenile Salmonids:
Oncorhynchus kisutch	*Oncorhynchus kisutch*	*Oncorhynchus gorbuscha*
Oncorhynchus tshawytscha	*Oncorhynchus tshawytscha*	

Table 4. Suggested other species in the Northeast Pacific that might be **monitored, modeled and studied retrospectively** during U.S. GLOBEC studies.

CCS—Region II Central California	**CCS—Region I Oregon**	**CGOA—Prince William Sound Region**
Holoplankton:	Holoplankton:	Holoplankton:
all, but esp. dominant species	all, but esp. dominant species	all, but esp. dominant species
Meroplankton:	Meroplankton:	Meroplankton:
Cancer magister	*Cancer magister*	*Cancer magister*
Strongylocentrotus spp.	*Strongylocentrotus* spp.	*Strongylocentrotus* spp.
		Juvenile Salmon:
		Oncorhynchus keta
		Oncorhynchus nerka
Predators/Competitors:	Predators/Competitors:	Predators/Competitors:
Merluccius productus	*Merluccius productus*	*Theragra chalcogramma*
Engraulis mordax	*Engraulis mordax*	*Clupea pallasi*
Sardinops sagax	*Sardinops sagax*	Birds
Scomber japonicus	*Scomber japonicus*	Mammals
Cassin's Auklet, other Birds	Cassin's Auklet, other Birds	
Mammals	Mammals	

To meet the general goal of the U.S. GLOBEC Northeast Pacific program (see p. 18), **monitoring, modeling and retrospective data analysis should examine the broadest suite of species and issues** relevant to the effects of climate change on North Pacific coastal ecosystems. Table 4 lists additional species whose abundances could be examined during past and future periods, through retrospective analysis and monitoring, respectively.

Where appropriate, non-target fish or benthic species, like hake and mackerel in the CCS and pollock and herring in the CGOA, could be **studied with respect to their impact on the target species**, focusing on describing their distribution, abundance, and predation rates. Studies on non-target species (Table 4) may be justified when such studies will be **valuable for characterizing the nearshore environment** (e.g., mesoplankton stages of some of the benthic invertebrates, small pelagic fishes). For example, characterizing the variability in the physical and biological environment using multiple "transects" stretching from Monterey up around the basin to the Shelikof Strait (Kodiak Island) region (see the sections below on Monitoring and Process Studies) is a core component of the Northeast Pacific program. The distributions and settlement patterns of meroplanktonic larvae of adult benthic species (e.g., crabs, urchins, mussels, barnacles, etc.), even though they are not named as target species for full population-dynamics oriented process studies, should be monitored within these transect programs because of the details they will provide on the nearshore conditions, where salmon mortality is hypothesized to occur. Likewise, retrospective studies of small pelagic fish population fluctuations provide information on basin-scale climatic changes that appear to also affect salmon stocks (Fig 3).

Despite the emphasis in the program on juvenile salmon, U.S. GLOBEC hopes that sufficient data are collected on all components of the coastal Northeast Pacific ecosystem so that explicit comparisons can be made to the studies being conducted on Georges Bank in the Northwest Atlantic. This will clearly occur in the holozooplankton where similar species, *Calanus finmarchicus* in the Atlantic, and *Neocalanus* and *Calanus* in the Pacific are target species. Data collected on gadids, especially pollock in the CGOA, during the monitoring and process studies, even if they are not the target species, will be valuable for comparing to the gadids, cod and haddock, of the Atlantic. Such comparisons across the regional U.S. GLOBEC programs will provide a broader understanding of the processes structuring marine systems.

Some species of subarctic and transitional holoplankton (e.g., copepods *Eucalanus bungii*, *Calanus marshallae, Calanus pacificus*, *Metridia pacifica*; euphausiid *Euphausia pacifica, Thysanoessa spinifera*) are common in both the CCS and CGOA. *Euphausia pacifica*, for example, has centers of abundance in both the Gulf of Alaska and off central and southern California (Brinton 1962). Genetic studies on these stocks may be valuable in examining relationships between broad-scale circulation patterns and population structures. Other species of subarctic holoplankton (e.g., copepods *Neocalanus plumchrus, N. flemingeri*, euphausiid *Thysanoessa longipes*) are more restricted to the northern regions, rarely becoming abundant in the CCS.

Few fishes have natural ranges which encompass both the CCS (Oregonian-San Diegan Provinces) and CGOA (Boreal Province) regions of the eastern North Pacific. Within the salmon, sockeye, pink and chum predominate in the CGOA (Alaska and British Columbia), whereas, coho and chinook are the more important species further south (Washington, Oregon and California). U.S. GLOBEC will focus on pink salmon (*Oncorhynchus gorbuscha*) in the CGOA and coho (*Oncorhynchus kisutch*) and chinook (*Oncorhynchus tshawytscha*) salmon in the CCS. Other fish species will be studied where they compete with the salmon for food or prey upon the target juvenile salmon. Pollock (*Theragra chalcogramma*) and herring (*Clupea pallasi*) are important to the trophodynamic pathways in the CGOA ecosystem. Pollock are not found off Washington, Oregon and California. Herring are important in the northern realm of the CCS (off Vancouver Island), but are not as abundant and important ecologically further south (Schwiegert, 1995). The small pelagics of note in the south are the Pacific sardine (*Sardinops sagax*) and northern anchovy (*Engraulis mordax*), which off southern California have populations out of phase. Centers of spawning for both are south of Pt. Conception (or in the Columbia River plume for the northern population of *Engraulis*), but during the recent warm period (esp. post-1990), successful spawning has occurred further north off Oregon, Washington and perhaps, British Columbia. Pacific hake (*Merluccius productus*) are abundant over the shelf and slope from ca. 25° to 50°N.

Adult hake migrate to the northern end of their range during the summer, where they are important consumers, especially of euphausiids and herring (Tanasichuk et al. 1991). In the autumn they migrate ca. 2000 km equatorward to spawn (mostly in January to March) in the waters offshore of the Southern California Bight and Baja California (Bailey et al. 1982). Hollowed and Bailey (1989) show that year-class strength in hake is usually established within 1-3 months of spawning—i.e., during their periods in warm waters offshore of the southern California Bight. Birds and mammals are likely to be important predators on juvenile salmon, especially in the CGOA.

Monitoring

The following questions will be addressed by both monitoring and retrospective studies.

- **What are the characteristic modes of natural variability in the physical and biological processes in the CCS and CGOA?**

- **What are the most important processes affecting population distribution and abundance of the species listed in Tables 3 and 4 in the CCS and CGOA and how do the varying strengths of these processes affect the response? Physical rocesses might include the intensity, timing and persistence of upwelling, mixing, cross-shelf and alongshore transport, stratification, temperature and the timing of seasonal transitions. Biological processes include zooplankton production and juvenile salmon mortality caused by predators. Other factors, including the genetic composition of populations and how it varies spatially and temporally may also be explored.**

- **Is there evidence for linkage between processes (both physical and biological) occuring at shorter (event-to-seasonal) and longer (interannual-to-interdecadal) time scales?**

Frequent, long-term monitoring of the environment is the only way to adequately document changes—be they gradual (e.g., trends) or dramatic (e.g., regime shifts)—in the marine ecosystem. **If the monitoring component of the program now proposed by U.S. GLOBEC for the Northeast Pacific had been in place for the past twenty years, we might already have answers to several of the questions posed above**, and our understanding of how the coastal ocean ecosystem responded to the atmospheric shift in the late 1970s would be much greater. However, because there was no monitoring of the marine ecosystems north of the CalCOFI region on the west coast, we are unable to state with certainty how the ecosystem changed in response to this large-scale phenomenon.

Long-term monitoring will provide a link between the intensive, process-oriented studies from the CGOA and CCS sites and the larger-scale, longer period climate variations. Monitoring in the Northeast Pacific GLOBEC program will proceed differently than that done for the U.S. GLOBEC program in the Northwest Atlantic. In the Northeast Pacific program, the frequent sampling of multiple cross-shelf transects (from Prince William Sound to the Monterey region), coupled with observations from moorings, drifters, floats and ships-of-opportunity, will be the analog of the broad-scale shipboard surveys that are used to monitor conditions on Georges Bank in the Northwest Atlantic. The CGOA and CCS ecosystems are highly advective. Following well-defined populations for extended periods, as is done on Georges Bank, will be difficult.

Monitoring of the Northeast Pacific will include the collection of data from satellites, enhanced volunteer observing ship (VOS) programs, coastal stations, selected cross-shelf transects, nearshore and offshore buoys, subsurface moorings, near-surface drifters, and perhaps other technologies. We recommend that specific biological and physical observations be obtained at the basin (gyre) scale. This will enable the connection to be made between the large scale forcing and the regional process studies in the CGOA and CCS. Figure 10 provides a cartoon of the types of observations needed to make that connection. These larger-scale observations of the circulation and biology of the gyre are critical in connecting the coastal regions of the CCS and CGOA to basin-scale forcing and in understanding the covariability between these regions.

Regular occupation of a few selected transects is key to monitoring the ocean conditions and variability in the coastal regions of the Northeast Pacific. Satellite sensing and moored instrumentation are excellent tools for some observations, but many biological quantities require ship sampling. Quarterly or bimonthly sampling with large oceanographic vessels to 100-200 km offshore would be supplemented by more frequent sampling (perhaps monthly, or more frequently during critical times [e.g. spring bloom; spawning events; juvenile entry into coastal waters]) of the more nearshore end (out to perhaps 20-25 km) of these transects by smaller vessels. Frequent cruises on established lines will be needed for calibrating indirect measures from remote-instrumentation and to directly sample ecosystem components such as zooplankton abundance, species composition, abundance of juvenile salmon and their competitors and predators, that cannot be collected remotely. Observations from several transects in the Northeast Pacific will also help to relate the biological and physical observations from moorings to larger regions.

The requirement for frequent sampling of the transects places some constraints on the potential number and location of the transects. Nearby logistical support by marine field stations or laboratories could warrant transects in the following regions (South to North): Monterey (MLML; MBARI; PFEG), Point Reyes/Arena (Bodega Bay Laboratory of UC Davis), Mendocino Region (Humboldt State), Coos Bay (OIMB), Newport (NMFS; Hatfield Marine Science Center), Columbia River (Astoria NMFS Lab), La Perouse Bank (ongoing Canadian site), west coast of Vancouver Island (Bamfield Marine Station), Line P (irregular Canadian occupation by IOS), Auke Bay (University of Alaska; NMFS Lab), Prince William Sound/Seward (University of Alaska GAK line), and Kodiak Island (FOCI line 8 of the NMFS/PMEL). Establishing routine monitoring of physics and biology from any of these stations would be a major improvement over current assessment efforts. For reasonable along-coast coverage, the sites probably most appropriate and able to undertake routine transect monitoring are Monterey, Pt. Reyes/Arena, Coos Bay, Newport, Auke Bay and Seward (not including the Canadian sites).

Detailed U.S. GLOBEC process studies (described in a later section) should be done at several of these regional transects. The highest priority monitoring transects are those tied to the process studies. Thus, we would anticipate that a single cross-shelf transect of stations would be sampled at least quarterly, perhaps bimonthly, throughout the 7 years from large oceanographic vessels, with more frequent sampling nearshore (by smaller vessels) during that region's process-study year, and perhaps during the spring and summer of all years. Observations taken at the transect sites should include hydrography, currents, net sampling of zooplankton, hydroacoustics, purse-seining

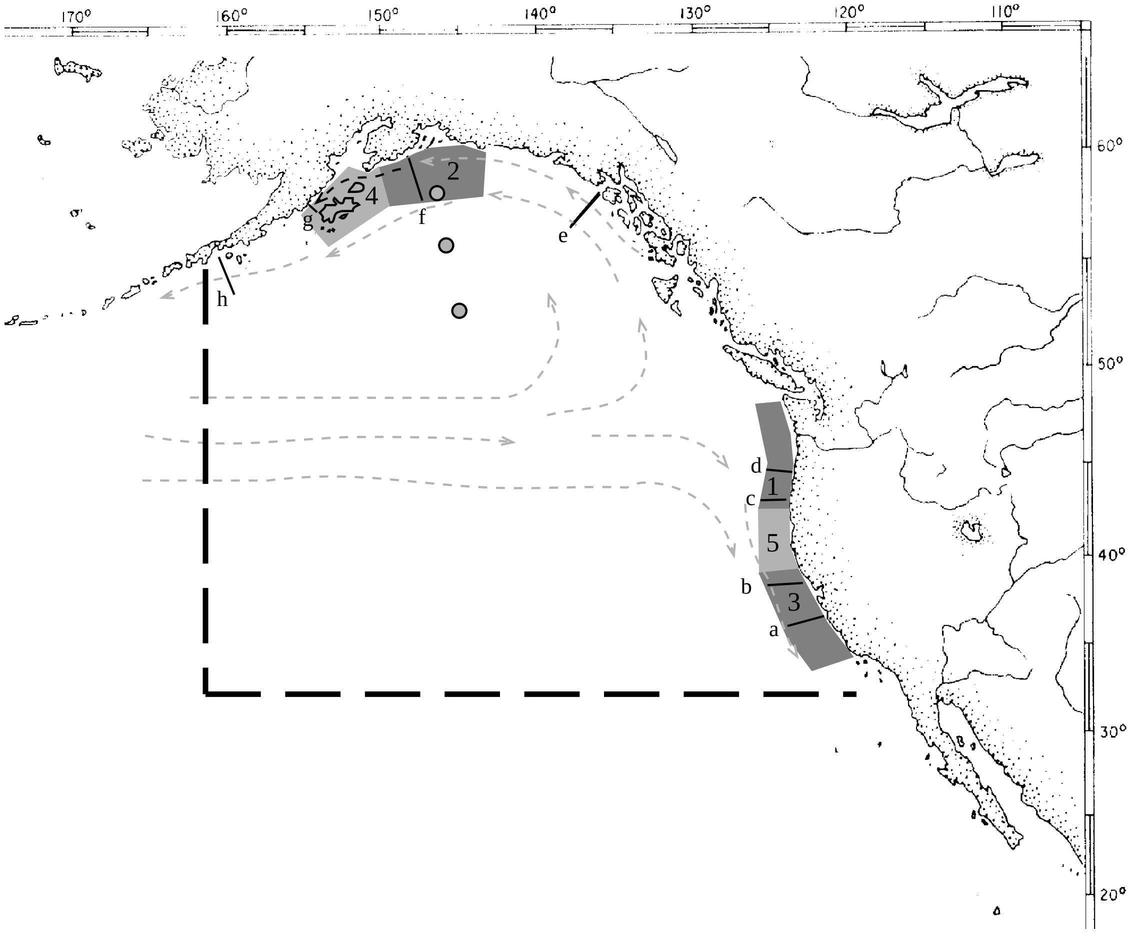


Figure 10. Schematic "cartoon" of potential observations to be conducted within the U.S. GLOBEC Northeast Pacific study. Regional process-studies (years labelled 1-5) are shaded. Potential monitoring transects (not exclusive) are shown as black lines and are labelled a-h. Also shown are three deep water moorings (large circles) in the Gulf of Alaska. Not shown are satellite observations, VOS sampling, PALACE floats, drifters, and details of sampling in process-study regions. PALACE floats and other Lagrangian instruments could be deployed within the region bounded by the dashed line.

(perhaps needed only in spring and summer), and ancillary observations. Drifters should be released as frequently as possible to describe the spatial and temporal variability in coastal ocean circulation. Because it is important that the observations be obtained consistently through time and in each of the various regions (e.g., transect sites), we recommend a core (minimum) set of measurements that should be obtained at each monitoring transect (Table 5). Consistency in sampling is crucial to making cross-regional comparisons and to facilitate time-series analysis. With the exception of the sampling of the salmon juveniles and other pelagic fishes (e.g., forage species) by purse-seining , all of the observations in the core program can be obtained from standard oceanographic research vessels. Sampling of the fish will require specially equipped vessels, either from the NOAA research fleet or chartered fishing vessels. Issues that arose in specifying the core monitoring measurements that should be addressed by the individual groups proposing to undertake transect monitoring and some quidelines on priorities for these issues are provide in Table 6.

Table 5. Minimum core measurements required and recommended protocols for the transect monitoring programs in the U.S. GLOBEC Northeast Pacific program.

GEAR	PROVIDES
1) CTD/Rosette Casts	• hydrography, mixed layer depths • transmittance, fluorometry, PAR • nutrient samples (NO_3, SiO_4, PO_4) • chlorophyll samples (total; <10μm fractions)
2) 150 kHz ADCP	• currents (detided where necessary) • bulk, depth-specific backscattering
3) Thru-hull (underway) surface observations	• temperature, salinity • fluorescence • particle size spectra
4) Vertical net hauls with appropriate gear and mesh (e.g., WP-2 net or similar with 150μm or 200 μm mesh); hauled vertically from within 5 m of the bottom or to 200 m (whichever is shallower)	• depth integrated (e.g., water column) abundances and biomass of holoplankton, meroplankton and some ichthyoplankton • capture eggs and nauplii of target holozooplankters • subsamples must be preserved in alcohol for subsequent genetic analysis
5a) Hydroacoustics using a 3 frequency (38, 120, 200 kHz) dual (or split) beam system with echo integration	• euphausiid abundance, distribution, swarm statistics
5b) Bongo (70 cm diameter) with 505 μm mesh towed double-obliquely from within 5 m of the bottom or 200 m (maintains compatibility with CalCOFI)	• euphausiid abundance, distribution, species composition • subsamples must be preserved in alcohol for subsequent genetic analysis
6) Surface trawling with 3/4" mesh	• quantitative abundance estimates of juvenile salmon, forage fish, small pelagics, and other fish predators • provides samples for estimating growth, condition, age, stock identification (genetics)
7) WOCE Standard Drifters drogued at 15m	• provides passive displacements • circulation statistics
8) Seabird and marine mammal predator observations	• seabird abundance, distribution estimates using strip-transect methods • marine mammal abundance, distribution estimates using line-transect methods

Table 6. Guidelines/priorities on several issues related to transect monitoring programs in the Northeast Pacific.

Issue	Recommendation	Rationale
1) Depth stratified sampling of plankton, krill and fish	• not recommended for routine monitoring • depth stratified sampling is more appropriate for process-oriented cruises	logistical constraints of: • sampling from small coastal vessels • ensuring comparable methods among all transects • post-cruise processing time and expense
2) Day vs. night sampling of plankton, krill and fish	• highest priority is daytime sampling of plankton & euphausiids at nearshore (within 30 km of the coast) stations • nighttime sampling of plankton & euphausiids are welcome supplements, but secondary to daytime sampling • fish sampling (trawling) can be done during either (or both) day and night	• some of the smaller vessels that will be used to sample plankton & euphausiids more frequently (e.g., monthly) along some transects are capable of working only nearshore and only during the day
3) Fixed station sampling vs. feature sampling	• highest priority is sampling of fixed location stations • additional sampling of features advantageous, but only as supplemental to fixed locations • sampling based on the positions of physical (fronts) or biological (swarms, etc.) is more appropriate to process cruises	• time series analysis techniques require repeated sampling at fixed station locations
4) Along-shelf variability	• fixed stations along offshore transect have highest priority • time-permitting, it is desirable to extent transect lines "offline" to estimate alongshore variability	• statistically valid time series analysis requires resampling of fixed stations
5a) Coordination of multiple vessels 5b) Coordination of research at multiple sites	• coordination (e.g., simultaneous sampling of transect) of oceanographic and trawling vessels desired to reduce sampling effort on plankton and physics components • select consistent methods; intercalibrate instruments	• if not coordinated, CTD and plankton sampling will need to be done from the trawling vessel (as well as the oceanographic vessel) • fewer samples => short processing time and lower expense
6) Offshore extent of sampling	• sufficient distance offshore to occupy two stations in water with depths of at least 500 m OR to capture most interesting/important dynamics	• in Region I of CCS, with narrow shelf and linear, alongshore jet--ca. 150 km from coast • in Region II of CCS, with complex mesoscale circulations--ca. 300 km from shore • in CGOA regions, with broader shelf--ca. 300 km from shore
7) Confirmation of acoustic target identities	• must be done by net sampling for euphausiids and trawling for fish	• multispecies assemblage of acoustic scatterers requires taxonomic confirmation of targets

Satellite data (AVHRR, SAR, color, altimeter, and offshore scatterometer) and ships of opportunity (or Volunteer Observing Ships, VOS) should be used to monitor large-scale, low-frequency variations of the North Pacific, Coastal Gulf of Alaska, and California Current. Since satellites can only sense the upper ocean, and for some parameters are limited by the cloudiness in the northern regions, the VOS observations will be critical to providing adequate seasonal, geographic and vertical coverage. VOS's should be used to expand geographic sampling coverage in the North Pacific beyond that of the nearshore and offshore mooring locations and drifters. Ships that routinely cross the Alaskan Gyre enroute from Valdez, AK to Hawaii could tow a high-speed undulating instrument, perhaps at a monthly frequency. There may be other routes (e.g., regular routes out of San Francisco, Long Beach, Portland, etc.) that could be exploited as well. Fishing vessels which ply the waters of both the CGOA and CCS could be equipped with appropriate equipment to monitor surface conditions on pump-through systems, and might even be encouraged to sample plankton. Nets on commercial fishing vessels could be equipped with inexpensive temperature-depth recorders to provide additional subsurface data. Efforts to equip fishing boats in this fashion are currently underway in the NW Atlantic region.

Observations of solar radiation, wind speed and direction, atmospheric pressure, air and water temperature, humidity, salinity and sea level height should be continued at existing monitoring sites in the North Pacific, and initiated at new locations near the regional process study sites. Some extensive monitoring is ongoing already. The TOGA/TAO array along the equatorical Pacific provides a link to the ENSO, basin-scale variability. The CLIVAR/GOALS program will continue to monitor and predict ocean variability in the central equatorial Pacific, perhaps extending to the whole basin. This activity should feed into the monitoring since we want to understand the basin-scale connections of the regional-scale monitoring.

Nearshore and offshore surface buoys should be used to measure solar radiation, wind speed and direction, atmospheric pressure, sea-surface elevation, air temperature, hydrographic conditions at several depths, upper-ocean velocities, fluorescence and plankton abundance by acoustic backscatter or optical plankton counters at a few nearshore (1-10 km offshore) and offshore (100-200 km offshore) locations.

In order to monitor biological and physical conditions, several (preferably 3) deep water subsurface moorings should be located as a transect within the Alaskan Gyre. They should be located (1) off the shelf in deep water, adjacent to the CGOA study region, (2) near the center of the Alaskan Gyre, and, (3) at an intermediate location. Brodeur and Ware (1992) and Brodeur et al. (in press) observed that zooplankton abundance increased most markedly over decadal scale periods along the margins, rather than in the center, of the Gulf of Alaska. Multiple deep water moorings, spanning the central gyre to the margin, would provide the data necessary to document productivity shifts that might occur during the program. The emphasis of these moorings should be to provide first, long-term biological observations (e.g., using optics, fluorometers and/or acoustics), and second, physical observations. Moreover, the moorings would provide data required to assure that simulations of the circulation and ecosystem of the Northeast Pacific are accurate.

Additional subsurface moorings measuring water temperature, salinity, velocity, fluorescence, light transmission, solar radiation and zooplankton biomass (using acoustics or optics) should be deployed for the full 5-7 year Northeast Pacific program at a few key sites in each of the regional study regions. These moorings would complement additional "mobile" moorings deployed in the three study regions during the period of the process-oriented field investigations. Thus, just as an example, there might be six instrumented subsurface moorings (two off central California; two off Oregon; and two off the CGOA study site) maintained for 5-7 years. One of the latter could be the innermost "deep-water" mooring of the Alaskan Gyre transect.

One challenging aspect of this program is to link regional-scale variability revealed in process-oriented and monitoring studies conducted in the CGOA and CCS to large/basin-scale oceanic variability that likely forced the biological changes that have occurred over the past several decades. Given the size of the Northeast Pacific, the connection between basin and coastal biophysical dynamics must be accomplished by modeling. Judicious monitoring of essential oceanic features, however, is essential to assure that simulations are accurate. Further, such observations can also be assimilated into models to nudge their output closer to observed conditions.

We envision a strategy which includes both Eulerian and Lagrangian measurements and suggest the following approaches to monitor the large-scale oceanography of the Northeast Pacific. First, a series of three deepwater moorings from the margin to the center of the Alaskan Gyre have been described previously. Second, the Alaskan Stream is a pulse-point in the North Pacific circulation, where measurements provide an index of the strength and variability of the subarctic gyre. The Alaskan Stream current is spatially most stable and narrow west of Kodiak Island (Reed et al. 1991); several subsurface moorings located across the stream there could monitor current velocity, vertical structure and water properties. Third, a recently developed technology, Profiling Automated Lagrangian Circulation Explorers (PALACE) floats, may be appropriate for providing temperature and salinity fields for assimilation into models. These floats collect vertical profiles of temperature and salinity, and can perhaps be modified to measure other parameters (e.g., fluorescence). They are programmed to reside on a density surface (perhaps at 800 to 1000 m), from where they periodically ascend to the surface collecting environmental information. By remaining deep most of the time, they are not quickly advected away from their initial position. They remain at the surface (order 16-24 hours) long enough to transmit their profile data and position via ARGOS transmitters; their estimated lifetime is two years. Riser (1995) estimates that ca. 60 floats would provide enough data to produce objective maps of the subsurface thermal and motion fields at ca. 500 km resolution for the entire subarctic Pacific. Fourth, satellite-tracked buoys drogued at appropriate depths could provide information on circulation and mesoscale features. Observations of the entire eastern North Pacific basin using these or similar methods are needed to place the regional process studies within the larger scale context of the circulation and water mass characteristics of the Alaskan Gyre, subtropical Gyre, and the bifurcation of the west wind drift as it nears North America.

It is unclear exactly how a monitoring program of the Northeast Pacific should be done—e.g., frequency of monitoring, state variables and rates to be monitored, and the most appropriate methodologies. To better answer these questions and to provide advice for more extensive monitoring in the future, we recommend that monitoring of the Northeast Pacific begin with a relatively modest pilot study. Despite the modest level of initial support for monitoring anticipated initially, we envision that this pilot monitoring include at least two transect lines: one north of the west-wind drift (CGOA), and one south of the west-wind drift (CCS). Tables 5 and 6 describe the minimum set of core measurements that would constitute an acceptable pilot monitoring program. Potential investigators are encouraged to propose ancillary measurements, in addition to the minimal set, that can be readily collected in an efficient and cost-effective fashion. Efforts should be made to cross-reference monitored quantities to other measurement efforts, past or present. Where feasible, monitoring data should be made available in real time, so that opportunistic studies can be conducted within a known physical and biological context. Further, consideration of the statistical power of the monitoring program, including some measure of the statistical properties of estimators derived from the monitored quantities, is advised.

Retrospective Data Analysis

To augment the new data that will be collected during the monitoring and process-study components of the U.S. GLOBEC Northeast Pacific study, existing data (whether it is on paper, in computers, or in jars) should be more thoroughly analyzed than it has been. The focus of retrospective analysis should be on addressing the same questions that are the focus of the monitoring component (see page), which relate to documenting natural variability in the ecosystems, and examining linkages between processes occurring at different time scales. Even widely used data sets such as the CalCOFI and COADS data could be more fully exploited for understanding ecosystem processes. Another type of data that could be explored is that recorded by the organisms themselves. One example is the records of fish scale and microscopic organism abundances from layered anaerobic sediments—some of these records extend into the past for thousands of years, with time resolution of a few years. Another example is the records of growth recorded in fish scales and otoliths. For salmon in particular, scales have been collected from fish for over 50 years. Those scale data could be used to examine how growth may have varied through time, perhaps in response to large-scale shifts in climate and ocean conditions.

Archived scales, otoliths or zooplankton samples could be used as sources of DNA to examine spatial and temporal patterns of genetic variability in the Northeast Pacific. Genetic variation that might exist among populations of species that span the two gyres could reflect another important aspect of coupling (or the lack of it) between the two systems. If populations of holo- or meroplanktonic species are differentiated across the two regions, this would imply barriers to genetic mixing, and possibly, different adaptive regimes in the two areas. Conversely, genetic homogeneity among regions would imply significant genetic mixing between them. Determining which situation (genetic differentiation vs. homogeneity) prevails could lead to insights regarding the relationship between broad-scale circulation patterns and population structures. It would also provide important baseline information for comparative studies between the two regions.

Prior U.S. GLOBEC reports (see esp. U.S. GLOBEC Rept. 11, 1994 and U.S. GLOBEC Rept. 15, 1996) review the types of data sets available for retrospective examination of the links between climate, physics and marine animal populations. Those sets include: 1) repetitive observations from satellites [e.g., AVHRR for SST; CZCS, OCTS (and future SeaWifs) for ocean color; altimeter for sea level height and geostrophic surface circulation; scatterometer for winds]; 2) time-series of point and gridded instrumental observations [e.g., sea level stations, buoy data, shore-based SST and salinity data, COADS, MOODS, precipitation and stream-flow records, FNMOC winds and pressure, climatic indices such as ENSO, upwelling, Aleutian Low]; 3) ocean surveys of in-situ biophysical data [e.g., CalCOFI survey, Ocean Station P, La Parouse program, Newport, OR hydrographic line; GAK 1]; 4) historical records of animal population changes [e.g., fisheries catch data, marine bird and mammal censuses, Japanese vessel survey data, Ocean Station P data]; 5) time series reconstructed from paleoecological data contained within marine sediments [e.g., fish abundance records from scales; microorganisms abundance patterns; perhaps measures of upwelling intensity from isotopic composition of organism hard parts].

Modeling

Modeling has been a central element of U.S. GLOBEC programs for a variety of reasons. Foremost, is the fact that by its very nature, the fundamental goal of U.S. GLOBEC—to predict the effects of future climate change—requires a predictive model. Models are the means of understanding complex interactions and projecting this understanding into the future for use in, for example, fisheries recruitment prediction. The Northeast Pacific program will generate information and understanding from a variety of disciplines (e.g., biology, physical oceanography, atmospheric sciences), a range of temporal and spatial scales, and several levels of biological organization (i.e, individual bioenergetics, population dynamics, food web interactions). Models will be required to integrate these so that the information can be used to project the consequences of likely climate change. To do this, we need models that span the range from the scale of basin-wide and decadal changes such as regime shifts to the scale of individual diel planktonic movement over meters. Modeling studies will be closely coordinated with monitoring, retrospective analysis and process studies. Building on the experience on Georges Bank, the large-scale modeling will be one of the first activities of the program. This early start is important to capture climate scale variability, set the boundary conditions for regional-scale models and the process studies, and recommend representative monitoring tactics.

In addition, models in this program will function as essential elements of the scientific efforts. Here too, they will serve to integrate various types of information, but the goals will be different. They will be used to test hypotheses, to determine sensitivities, to plan research, and to evaluate the results of interdisciplinary research.

To meet the general goals of the U.S. GLOBEC Northeast Pacific program, the models can focus on the broadest suite of species and issues relevant to the effects of climate change on North Pacific coastal ecosystems. Modeling studies may be developed with a focus on species targeted for the process studies (Table 3) or other non-targeted species, which could be sampled in the monitoring or analyzed in retrospective studies (Table 4).

Development of models well in advance of any field investigations has been an explicit goal of the U.S. GLOBEC program. An earlier U.S. GLOBEC workshop on secondary production modeling identified five <u>general</u> issues which are critical to predictive modeling that couples physical and biological processes (U.S. GLOBEC 1995).

- The role of organism motility (independent of the fluid medium), especially for the higher trophic level populations on which GLOBEC focuses. Several of the target organisms are more than passive floaters—they make choices such as vertical migration, swarming, etc.—and this has implications for transport, retention in favorable habitats, growth and survival.

- Differences in trophic organization—for example, food webs with gelatinous zooplankton as top predators, compared to those with carnivores, like salmon, at the highest trophic level.

- The coupling of processes acting at different spatial and temporal scales, as well as different levels of organization. An ultimate goal is the development of large- or basin-scale models that are coupled to more-detailed regional-scale biophysical models, and are capable of forecasting effects of climate changes on the zooplankton and fish populations.

- The incorporation of data into models, and the converse activity of utilizing model results to plan and to interpret field and laboratory studies.

- The availability of coupled biological-physical models to the larger community, and a broad-based community modeling effort with an enduring funding commitment.

Planning activities for the Northeast Pacific program (U.S. GLOBEC Report No. 11, 1994; and U.S. GLOBEC Report No. 15, 1996) have identified four specific modeling efforts that are needed to address these general issues.

- Basin-scale general circulation modeling with higher-resolution, nested coastal biological-physical components. A link to entire North Pacific simulations that are coupled to large scale atmospheric models would be desirable, especially for hindcasting studies.

- Regional-scale coupled biological-physical models. The best of these endeavors would aim to assimilate available observations (e.g., remote sensing data, buoy data, etc.), resolving the exchange of water and organisms between the coastal shelf and deeper oceanic waters.

- Coupled (mesoscale) biological-physical formulations. Models of this type should aim to resolve fronts, include mixed-layer dynamics, possibly address the shallow, turbulent inner shelf, and operate over diurnal time scales. They might address the separation of the upwelling front from the coast, including the relative roles of topographic irregularities and wind forcing. They should incorporate coastal transport processes and detailed biology, including food web relations and organism behavior.

- Modeling efforts that investigate the response of biological metapopulations to spatially and temporally varying physical forcing (Botsford et al. 1994). Some attention should be paid to models with very detailed biology, and less detailed physical transport. Examples might include bioenergetic models of juvenile salmon, predator relations, seasonal prey switching behavior, and/or nearshore food web dynamics for several different environmental scenarios. Some of these issues might best be addressed by individual-based models.

Several necessary lines of investigation cut across these model types. For example, the functional details of how to parameterize individual interactions between organisms (e.g., predator-prey) is a challenge to modelers at all scales. Moreover, how one might embed a regional model of coupled biological-physical processes within a basin-scale circulation model, or a mesoscale formulation within a regional model, remains a challenge. Technical concerns, like the specification of boundary conditions, particularly along open boundary segments, are far from settled at any scale. The assimilation of biological data into models of all kinds is another unsolved (and barely addressed) problem. Finally, models need to be verified, for it is only verified models that are of ultimate use.

A significant constraint on future progress is the lack of reliable and generally accepted coupled models available to the research community at large. Few users can be found even for those models for which some level of reliability can be claimed. To remedy this situation will demand resources for community model development and testing, and a commitment to the user communities. Rapid response to these widely acknowledged needs would allow the broader community to take advantage of opportunities represented by recent improvements in computer architectures, high-speed networking capabilities, and hierarchical data management and retrieval systems.

Process Studies

The sites of process-oriented field research in U.S. GLOBEC investigations in the Northeast Pacific will be closely linked to the transect locations where long-term, frequent monitoring of the atmospheric forcing, physical structure and circulation, and biological observations will be done. Likely sites were described in the monitoring section. The overarching questions for the process-oriented investigations in the Northeast Pacific are:

1) **How are biological processes and the characteristics of planktonic populations affected by mesoscale features and dynamics in the Northeast Pacific?**

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

Related to these questions are a number of sub-questions specific to either the CCS and CGOA. These primary questions and the sub-questions specific to the two regions are discussed in the sections below.

California Current System

In the CCS, U.S. GLOBEC will examine the linkage between growth, reproduction, mortality, genetic composition, physiological condition, transport, and recruitment of zooplankton and juvenile salmon and the dominant spatial and temporal variability of physical forcing. U.S. GLOBEC assumes that overall secondary productivity of the nearshore system is connected (in ways that still need to be deciphered) to both the growth and survival of juvenile salmonids during their first few months in the ocean, and thus to year-class strength of the returning adults. From the timeline (page 24), note that there will be three years (Years 3, 5, and 7) of process studies in the California Current System (CCS). Large-scale latitudinal gradients in mesoscale dynamics will be investigated by focusing similar process studies in Region I and Region II of the CCS in field years 3 and 5, respectively. The site for the Region I studies in Year 3 will be off central Oregon. The site for Region II studies in Year 5 will be off north/central California. In Year 7, U.S. GLOBEC proposes a Lagrangian study in which water and/or organisms (tagged) in the alongshore, southward flowing jet in Region I (off central Oregon) are followed (and repeatedly sampled) as the jet transits offshore (near Cape Blanco), and meanders offshore of Northern California.

Some aspects of U.S. GLOBEC's proposed studies in the Oregon and Northern California region will be done in collaboration with the Coastal Ocean Processes (CoOP) program's investigation of cross-shelf exchanges in wind-driven regions. CoOP proposes to use modeling and intensive process studies in Regions I and II of the CCS to examine the processes that control the cross-margin transport of biological, chemical and geological materials in a strongly wind-driven system (Smith and Brink 1994). Although the alongshore coastal winds are the dominant forcing from the northwest tip of Washington (48°N) to Point Conception (35°N) in southern California, there is a significant difference north and south of about 40°N. During summer, the alongshore winds are strongly favorable for coastal upwelling but more variable north of about 40°N. During winter, low pressure systems from the Gulf of Alaska cause a strong northward component in the coastal winds and downwelling along the coast of Oregon and

Washington. South of San Francisco (37°N) upwelling generally continues intermittently, interrupted by occasional winter storms. These differences in forcing and response form a natural laboratory within which processes responsible for wind-driven cross-shelf transport can be studied intensively and incorporated into theoretical, numerical and laboratory models of these systems. Since coastal upwelling and downwelling are the ubiquitous coastal responses to surface boundary layer transports forced by local alongshore winds, these processes have more than regional importance in understanding cross-margin transport (Huyer, 1990).

CoOP has recommended that parallel studies north and south of about 40°N be made, with possible locations being central Oregon and northern California (Smith and Brink, 1994). The logistical ease, the oceanographic background from previous studies, and the relative simplicity of these regions (lack of major riverine, topographic, or tidal effects) makes them especially attractive for a CoOP study of wind-driven processes affecting cross-margin transport. For the past three years, the U.S. GLOBEC program has been discussing with CoOP ways to couple our studies of the CCS with those planned by that program. Linking U.S. GLOBEC and CoOP studies, where possible, will bring more expertise and greater resources to this effort than would be possible by either program alone. CoOP could bring detailed nearshore physical oceanography and larval studies (especially if meroplankton of adult nearshore species are used as tracers of cross-shelf exchange, as proposed by CoOP) to the broader spatial, temporal, and ecological studies proposed by U.S. GLOBEC.

U.S. GLOBEC's CCS process studies will be structured to address four questions:

- **How does changing climate, especially its impacts on local wind forcing and basin-scale currents, affect spatial and temporal variability in mesoscale circulation?**

- **How do mesoscale features in the California Current System impact zooplankton biomass, production, and distribution, and the retention and loss of zooplankton from coastal regions?**

- **How important are the levels of primary and secondary production and the intensity of cross-shelf transport associated with wind-driven upwelling in controlling juvenile salmon growth and survival in the coastal zone of the CCS?**

- **To what extent is high and variable predation mortality on juvenile coho and chinook salmon in the coastal region of the California Current responsible for the large interannual variation in adult salmon populations?**

The important biological processes include primary production; growth, mortality, fecundity and the genetic composition of zooplankton; transport, retention and recruitment; and links between secondary production, especially reproductive output, and the subsequent recruitment success of fish and benthos. Mesoscale physical processes expected to control these biological variables, and subject to change with changing climate, include frontal dynamics, upwelling, locally intense cross-shelf transport, eddy recirculation, stratification and vertical shear. Mesoscale features are the dominant variability in the Northern California section (Region II) of the CCS. In Region II, productivity and zooplankton abundances are probably highest inshore of the meandering jet region, in the region of most intense upwelling, but the habitat used by the salmon off of Northern California is not known. Nearshore circulation in Region I is less complex than in Region II. The upwelling zone extends only ca. 50 km from the shore, but upwelling is most intense within 15 km of the shore. Phytoplankton, zooplankton, fish larvae and juvenile salmonids are most abundant within the nearshore region of greatest upwelling.

Recent evidence (Huyer et al. 1991; Washburn et al. 1993) suggests that much of the advection within Region II of the CCS occurs in mesoscale features, which also may affect the local intensities of upwelling, downwelling, mixing and primary productivity. Large scale forcing, operating through both the ocean (e.g., advection from the north and south) and the atmosphere (variations in wind intensity, direction or duration), must be important to these mesoscale features, but the mechanistic linkages between the large- and meso-scales are not known. Satellite SST images off central California led Schwing et al. (1991, p. 57) to conclude:

> "The impression gained from a series of satellite images of the study area is that several general water masses, indicated by surface temperature, are present at all times, but their relative and absolute location can change on short subsynoptic time scales not detected by traditional ship-survey methods. These changes could profoundly affect the biota in the region..."

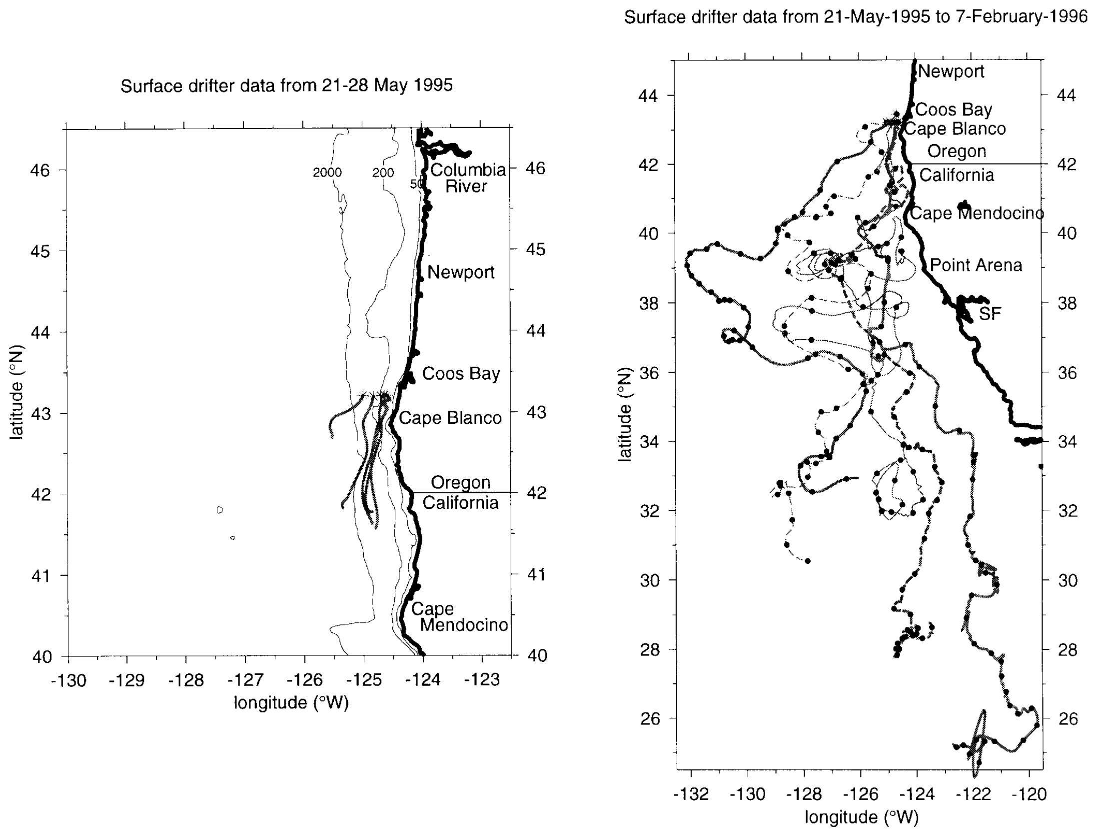
Mesoscale features (i.e., eddies, jets, etc.) may be retention sites (via physical means) or aggregation sites (via behavioral means) for zooplanktonic populations (Huntley et al. 1995). If individual demographic parameters (e.g., the vital rates of birth, growth and death) differ inside and outside these features, this can have significant impacts on population growth rate and production. Frontal zones associated with the mesoscale features may be sites of enhanced primary production and concentration of planktonic prey, and therefore favor zooplankton growth and fecundity. Conversely, if predators accumulate at the fronts to better utilize their prey, zooplankton survival may decrease. Upwelling, especially its intensity and persistence (or conversely, intermittence), can have important impacts on the productivity of the nearshore ecosystem, and the ability of secondary consumers to efficiently utilize upwelling enhanced primary production (Attwood and Peterson 1989; Peterson et al. 1988). Timing of the spring transition in relation to the period of nearshore spawning of benthic invertebrates and the arrival of salmon from their natal streams (or hatcheries) may be critical in determining growth and survival.

During the spring and summer, species with long pelagic larval stages are likely to be transported substantial distances southward (the "mean" flow direction). Mesoscale features, which persist temporally, or are spatially predictable, may be one mechanism for maintaining larvae near their source (Barth and Smith, in press). Another mechanism may be the interaction of behavior with transport processes. For instance, some marine zooplankton, e.g., *Calanus marshallae,* in Region I employ vertical migration behavior and ontogenetic changes in vertical distribution that interact with vertical current shear to reduce offshore transport and increase their residence time in the coastal zone (Peterson et al. 1979). U.S. GLOBEC studies in this region should examine how behavioral attributes of the resident fauna control their retention in a region with strong alongshore advection.

Most of the biological impacts of mesoscale features and dynamics discussed above relate to spatial and temporal variability in the patterns of secondary (e.g., zooplankton) production. These processes may be equally important to consumer species (i.e., salmon). There are related questions that could also be addressed by U.S. GLOBEC studies off of Oregon and California. What are the implications of the mesoscale structure (and variation in the structure) in permitting different suites of higher trophic level organisms (e.g., perhaps predators of salmon) to occupy the nearshore regions? For instance, in some El Niño years, the advection of warmer waters from the south permit warm-water predators to "invade" normally cold habitats off northern California and Oregon. Warmer offshore waters brought inshore by eddies may have similar impacts, either directly (by introducing additional predators) or indirectly (by compressing favorable salmon habitat to smaller regions, which can be more effectively exploited by nearshore consumers). In addition to these impacts on the growth and survival of the target species (i.e., salmon), there may be direct impacts on higher trophic level productivities, distribution, and abundance. Another issue that could be addressed deals with genetic and demographic differences in the populations. Coho and chinook salmon exhibit both inter- and intra-specific life-history variation (Groot and Margolis, 1991; Mangel, 1994). Some of the variability (e.g., age at maturity, timing of spawning, migration behavior) may be linked to genetic and geographic factors. Perhaps some is also controlled by environmental variability; for example, by the certainty of encountering, or the location, of salinity fronts at the mouths of coastal streams as salmon emerge from the estuaries. Small-scale environmental conditions may interact with a range of genetically programmed responses, resulting in specific "habitat selection" behaviors. The last two questions (above) consider whether salmon survival during the ocean phase of the life history is controlled from the bottom-up (through food availability) or from the top-down (through predation relations) during the juvenile period in the coastal ocean.

Pearcy (1992) recently reviewed the ecology of juvenile coho salmon in the nearshore waters of Oregon and Washington (Region I). Studies of juvenile coho conducted over five years in the 1970's indicate that they are not highly migratory, remaining nearshore within the upwelling zone through much of their first summer in the ocean. Ocean survival was positively correlated with upwelling during the period immediately after ocean entrance before the 1976-77 shift in ocean conditions. Most juvenile coho appear to be swept southwards in the mean coastal flow during May and June upwelling, when the mean coastal flow is strong to the south, and when the smolts are smallest and weak swimmers. Later in the summer, most of the juvenile coho, now larger and stronger swimmers, are able to swim northward against the weaker southward flow (Pearcy and Fisher, 1988). It also appears that the critical period that determines eventual year-class strength most likely occurs early in ocean life, perhaps within the first month of ocean residence. This is suggested by the high correlation of eventual year-class strength with early returns of precocious males (jacks) (Fisher and Pearcy, 1988). The mechanistic coupling of coho salmon survival with coastal upwelling is unknown at present and will be a focus of U.S. GLOBEC studies in the CCS.

In Region II (south of Cape Blanco), little is known about the marine habitats used by coho juveniles. After the spring transition, southward velocities in the jet off Oregon are commonly 10-20 km/day and can reach 50 km/day (Barth and Smith, submitted). Trajectories of drifters released into the jet north of Cape Blanco vary seasonally. Drifters deployed in May (during well developed upwelling) are rapidly advected southward and offshore in the vicinity of Cape Mendocino and Point Arena (Fig. 11); during an August period of rather weak equatorward (upwelling favorable)


Surface drifter data from 21-28 May 1995

Surface drifter data from 21-May-1995 to 7-February-1996

Figure 11. Trajectories of five satellite-tracked surface, near-surface drogued drifters released on 21 May 1995 off Coos Bay, Oregon. Marks along the drifter tracks are at weekly intervals. Drifter tracks are shown for (left) one week and (right) 8 1/2 months after the release. The drifter released second farthest west failed on 30 May 1995. An additional drifter (thin dashed curve) is included in the right panel beginning on 31 May 1995 just to the north of the earlier five-drifter release latitude. (from Barth and Smith, submitted).

winds, drifters moved offshore into either a recirculating eddy region or a quiescent region, later returning to shore at nearly the same latitude as they departed the coast (Barth and Smith, submitted). This spatial and temporal variation in the strength of alongshore transport can have implications on early salmon survival; food and predator environments of the salmon juveniles may differ depending on phasing of salmon entry to the ocean and the spring transition. Mesoscale features in physics, primary production, and zooplankton distribution and production may be important to the growth and survival of juvenile coho and chinook in this region of the CCS.

Studies of mesoscale processes and their impacts on zooplankton distribution, and productivity (see above), will include measurements of juvenile salmon distributions, growth (and survival from marked fish) at selected sites in Region I (Newport, OR) (Year 1), Region II (Pt. Reyes/Arena or Monterey region) (Year 3), and as a Lagrangian flow through study of both regions I and II (Year 5). All elements (zooplankton and salmon juveniles) will be studied in each process study. These studies of the CCS may include the following components:

- Collection of meteorological, physical and biological data by satellite and shore-based remote sensors, drifters and fixed moorings. New technologies, such as the use of shore-based radars (OSCR, CODAR) could be applied to long-term study of mesoscale and smaller-scale (1 km resolution) variability in upper ocean circulation patterns. It may be possible to monitor frontal genesis in near-real time, so that shipboard physical and biological sampling can be directed by accurate "charts" of surface circulation and fronts.

- Repeated at-sea sampling of plankton, fishes, hydrographic and nutrient data. Abundances of target species should be quantified using depth stratified sampling with nets, acoustics and optical devices. Purse seining or midwater trawling (using specially equipped vessels) will be required to sample juvenile salmon and their predators and competitors. Temperature, salinity and advection should be measured using "towyo" CTD, SEASOAR, and shipboard ADCP. Both Eulerian-frame (fixed grid and feature oriented) sampling and Lagrangian-frame (following tagged water parcels and/or specific populations) sampling will be employed. A key process for examination will be the interaction of mesoscale transport processes and recruitment (or other measures of population success) of the key species—i.e., how do the community composition, and vital rates and population structure of the target species vary with location (e.g., within the core of a jet, or in upwelling or downwelling sides of meanders, etc.). Details of the sampling will need to be based on specific hypotheses about the life history requirements of particular species—i.e., the timing and spatial distribution of sampling will have to match the developmental and transport schedules of the selected species. Within the copepods, for instance, egg production rates, grazing rates, and development rates measured at stations located in different parts of the jets, filaments and meanders will indicate whether these mesoscale features impact secondary production and how important it might be for the organisms to select specific environments.

- Frequent nearshore (and perhaps offshore in Region II) sampling to document habitat selection and utilization by juvenile salmonids and their competitors and predators, and their relation to the physical dynamics (position of upwelling centers; frequency of wind reversals and associated onshore flow of surface waters; position, strength and variability of fronts). In addition this sampling will provide the samples for studies of the diet of juvenile coho, and provide information on the diet of other fish species that may be competitors or predators of the coho. Sampling should be conducted both at night and during the day.

- Interaction with the modeling activities (described in the modeling section) to parameterize organism vital rates and behaviors that permits their inclusion in models. It is important to compare the biological and physical predictions from models with measured responses to variations in physical forcing.

The sites of monitoring stations and the specific measurements obtained over the longer-term (5-7 year period) need to consider the observations that will be collected during the more intensive, process-oriented field year, so that the key physical processes and biological parameters are measured by comparable methods (see the section on monitoring).

Coastal Gulf of Alaska

U.S. GLOBEC developed a list of nineteen research questions for the CGOA (see pp. 64-65 of U.S. GLOBEC Report No. 15, 1996). In summary the questions addressed a few key themes: 1) the relationship between atmospheric forcing (including wind and precipitation [e.g., buoyancy effects]) and coastal circulation, mixed-layer depth and temperature, retention time scales, and cross-shelf transport; 2) the factors, both physical and biological, controlling primary productivity and the composition and production of plankton in the CGOA; 3) the impact of climate change on trophic phasing within the ecological food web of the region and especially its effect on over-wintering plankton distribution and biomass; and 4) the impacts of climate change on higher trophic levels (fish, birds, mammals), especially on their distribution, patchiness, growth, survival, reproduction, and seasonality.

A smaller group of scientists met later to further focus the discussions of the April 1995 workshop and produced the following overarching hypothesis for U.S. GLOBEC Coastal Gulf of Alaska research (U.S. GLOBEC, 1996b):

> Ocean survival of 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.

Detailed, process-oriented research and surveys in a focused coastal study were designed to address this hypothesis. In this implementation plan, U.S. GLOBEC emphasizes studies of the physical environment, plankton environment, and juvenile salmon. The specific questions that U.S. GLOBEC proposes to address through process-studies in the CGOA are:

- **How does changing climate, especially its impacts on local wind forcing and basin-scale currents, affect spatial and temporal variability in mesoscale circulation?**

- **How do mesoscale features in the Gulf of Alaska impact zooplankton biomass, production, and distribution, and the retention and loss of zooplankton from coastal regions?**

- **Is the cross-shelf import of large zooplankton (e.g., copepods and euphausiids) from deeper offshore regions to nearshore shallow waters in the spring required for rapid growth and high survival of juvenile pink salmon in the coastal Gulf of Alaska?**

- **To what extent is high and variable predation mortality on juvenile pink salmon in the coastal region of the Gulf of Alaska responsible for the large interannual variation in adult pink salmon populations?**

The first two questions are identical to the first two specified for the CCS. They consider climatic forcing and variability to variation in mesoscale circulation, which in turn may be a significant factor impacting plankton production dynamics and transport. As was the case in the CCS, the last two questions relate salmon survival in the ocean to bottom-up and top-down controls operating during the juvenile period while the salmon are nearshore, although because the CGOA is predominantly a downwelling system, the mechanistic details differ (especially for bottom-up control). U.S. GLOBEC recommends that Year 4 studies in the CGOA focus primarily on bottom-up control, and the plan detailed below reflects that selection. The emphasis on bottom-up processes, however, does not mean that concurrent data on top-down processes should not be collected during Year 4. Such data should be obtained if it does not interfere with the primary research. Moreover, data on the structure and variation of the physical environment and the plankton environment should be collected in all process-study years. With these thoughts in mind, we provide background related to potential bottom-up control of juvenile pink salmon survival in the CGOA.

In Prince William Sound, Alaska, a mid-spring bloom of *Neocalanus* biomass corresponds closely to the timing of outmigrating pink salmon fry (Cooney et al. 1995). The diet of the juveniles over the shelf after they leave PWS is not well known, but it is likely that the large interzonal copepods and euphausiids are important forage items for many species residing on the shelf. Cooney (1986b, p. 293-294) notes,

> "Cooney (1986a) demonstrates the seasonal presence of the oceanic interzonal copepods over the shelf of the northern Gulf of Alaska. This presence is associated both with the time these species reside in the wind-influenced surface layer of the bordering ocean and with the duration of the shelf convergence season that lasts from October to April each year (Royer 1981). These and other oceanic zooplankters are dominant members of the shelf and coastal communities, a fact that adds support to the notion that the bordering ocean may be the source for substantial amounts of organic matter that is advected shoreward in the seasonally persistent onshore Ekman flow (Cooney 1984). . . . The considerably narrower shelf of the Gulf of Alaska has a much more advective environment due to influences by both the Alaska Current over and along the shelf break, and by the Alaska Coastal Current (ACC) that occupies the first 40 km from the beach seaward. . . . Interactions between these two currents (where the shelf is < 50 km wide) presumably provides a mechanism to mix and transport the coastal and oceanic faunas over and along the shelf. This mechanism, combined with the wind-induced onshore Ekman flow, assures that near-surface (upper 200 m) zooplankters of oceanic origin become a seasonal part of the shelf/coastal zooplankton communities."

The exact mechanism of the coupling between the *Neocalanus* and salmon juveniles on the shelf, and whether it is direct or indirect, is not known. The impact could be direct in that the copepods (esp. *Neocalanus*) transported onshore, or their progeny, are important prey of the juvenile pink salmon, thus promoting rapid growth and higher survival. Alternatively, the import of zooplankton biomass may have an indirect effect by presenting an alternative prey to potential consumers of juvenile salmonids, such as herring and pollock. In that case, large quantities of zooplankton prey may improve juvenile salmon survival by reducing predator related mortality. The primary physical processes which contribute to influx, retention and exchange of water, nutrients and plankton on the continental shelf of Alaska are the buoyancy-driven and wind-forced transports near-shore, and interaction with the gyre-scale Alaska Current off the shelf.

U.S. GLOBEC recommends that a process-oriented investigation of the food web shown in Figure 12, 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. Prince William Sound has large wild and hatchery-released stocks of pink salmon. Approximately 450 million hatchery fry with distinctively thermally marked otoliths are released each year from the hatcheries within PWS. These join an approximately equal number of wild out-migrants from adjacent natal areas. It is believed that the fish remain in PWS for up to about two months before exiting onto the Alaskan continental shelf proper (Cooney 1993). Their residence time, food habits (diet), and the magnitude and sources of mortality while they are on the shelf are not known. 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 tags, thus it provides positive identification of the pink salmon source. Although Cooney and Willette (1996) observed similarly phased marine survivals of hatchery and native pink salmon stocks from PWS, studies of survival of wild and hatchery stocks of salmon from other regions indicate higher survival of wild salmon, perhaps due to different behaviors. Thus, some consideration of potential differential survival of hatchery reared and wild salmon may be needed during U.S. GLOBEC studies.

Collaboration with other programs is essential to meeting the objectives set for this year. Potential collaborators include the Exxon Valdez Oil Spill (EVOS) Trustees, that are currently funding the Sound Ecosystem Assessment (SEA) project investigation of the pelagic food web in Prince William Sound, AK, and the Ocean Carrying Capacity (OCC) program which is currently conducting annual shelf-wide trawling surveys for salmonids. U.S. GLOBEC proposes to conduct studies similar to those being conducted by SEA in PWS, but over a much larger region on the shelf (outside PWS), ranging from approximately 143°-150°W. The Alaska Coastal Current, which dominates the circulation on the shelf in this region flows from east to west in this region (Fig. 13). The box delimiting the study region is approximately 300 km alongshore and 150 km in the cross-shore direction. Reports from the OCSEAP (Outer Continental Shelf Environmental Assessment Program) program conducted during the mid-to-late 1970s summarize much of what is known about the ocean conditions and biology of this region (e.g., see the papers in Hood and Zimmerman 1986). The westernmost transect shown on Figure 13 is the Gulf of Alaska (GAK) line. Significant data on ocean physics exist for that line, with especially the innermost station (GAK1) having been sampled very frequently since 1970 (Royer, 1993). A hydrodynamic model of flow into, within and exiting PWS is being developed within the SEA program. Seeding of PWS with *Neocalanus* populations from offshore is of interest to that program. *Neocalanus* intrudes into PWS along with the other interzonal copepod, *Eucalanus bungii* (Cooney, 1986a), 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). Mesoscale features are observed on the Alaskan continental shelf (Fig. 14); for instance, there is a permanent eddy on the shelf, west of Kayak Island (Fig. 13), which may be important in determining residence times of some of the organisms on the shelf, even though it is "upstream" of PWS. Drifters deployed during the OCSEAP program in the ACC upstream of the eddy and PWS, made several loops of the eddy before being eventually advected further west and into PWS (Fig. 15). Clearly, transport along the

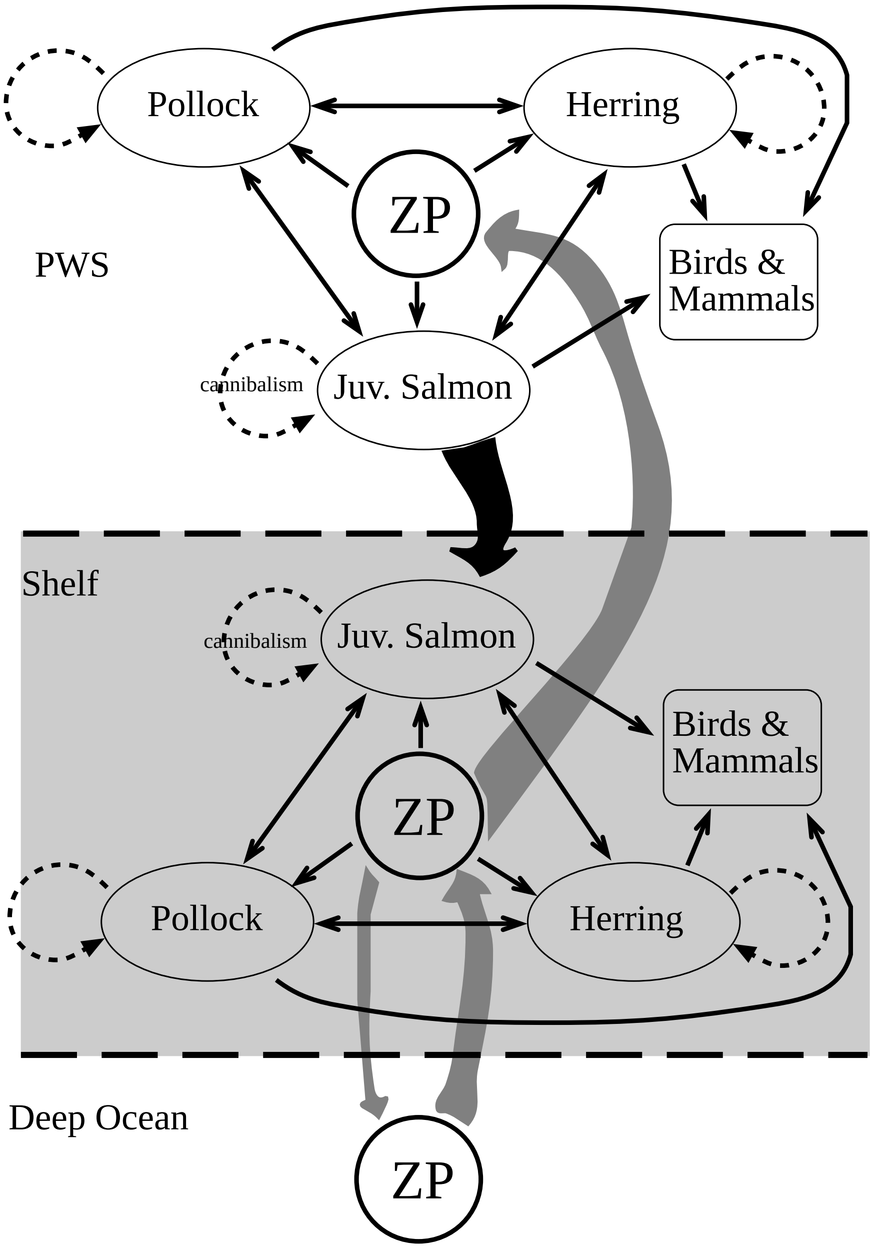


Figure 12. Schematic of the pelagic food webs within and on the shelf outside Prince William Sound, Alaska with herring, salmon (esp. juveniles), pollock, zooplankton (ZP), birds and mammals. Solid narrow arrows show trophic pathways between species. Dashed narrow arrows show cannibalism. Fat black arrow shows emmigration of juvenile salmon from PWS to the shelf. Fat gray arrows show exchanges of zooplankton between the deep ocean, shelf and PWS. That food web on the shelf (shaded) and the exchange of plankton and nutrients between the deep ocean and the shelf will be the focus of U.S. GLOBEC CGOA studies. (From U.S. GLOBEC Report No. 16; 1996).

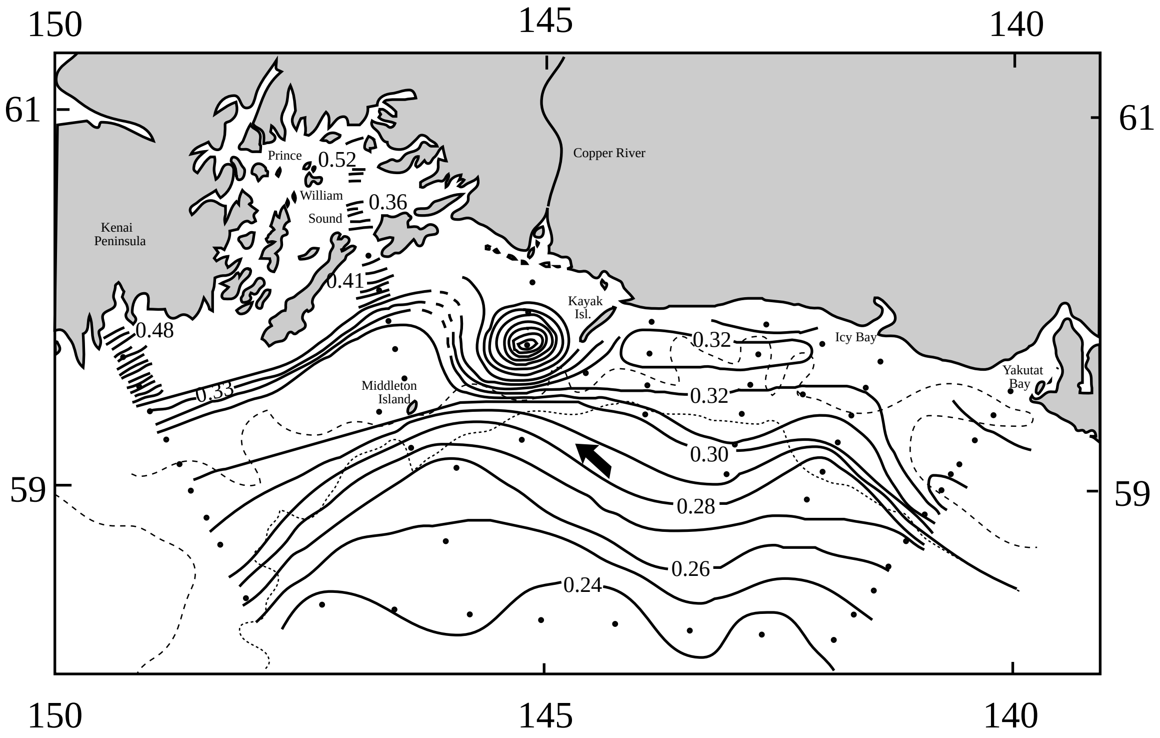


Figure 13. Geopotential topography (ΔD, dyn m) of the sea surface (1/100 db) during September 1976 on the shelf outside of Prince William Sound, Alaska. The 183 m and 1830 m depth contours are shown as broken lines. Arrow denotes direction of flow. (Redrawn from Reed and Schumacher, 1986).

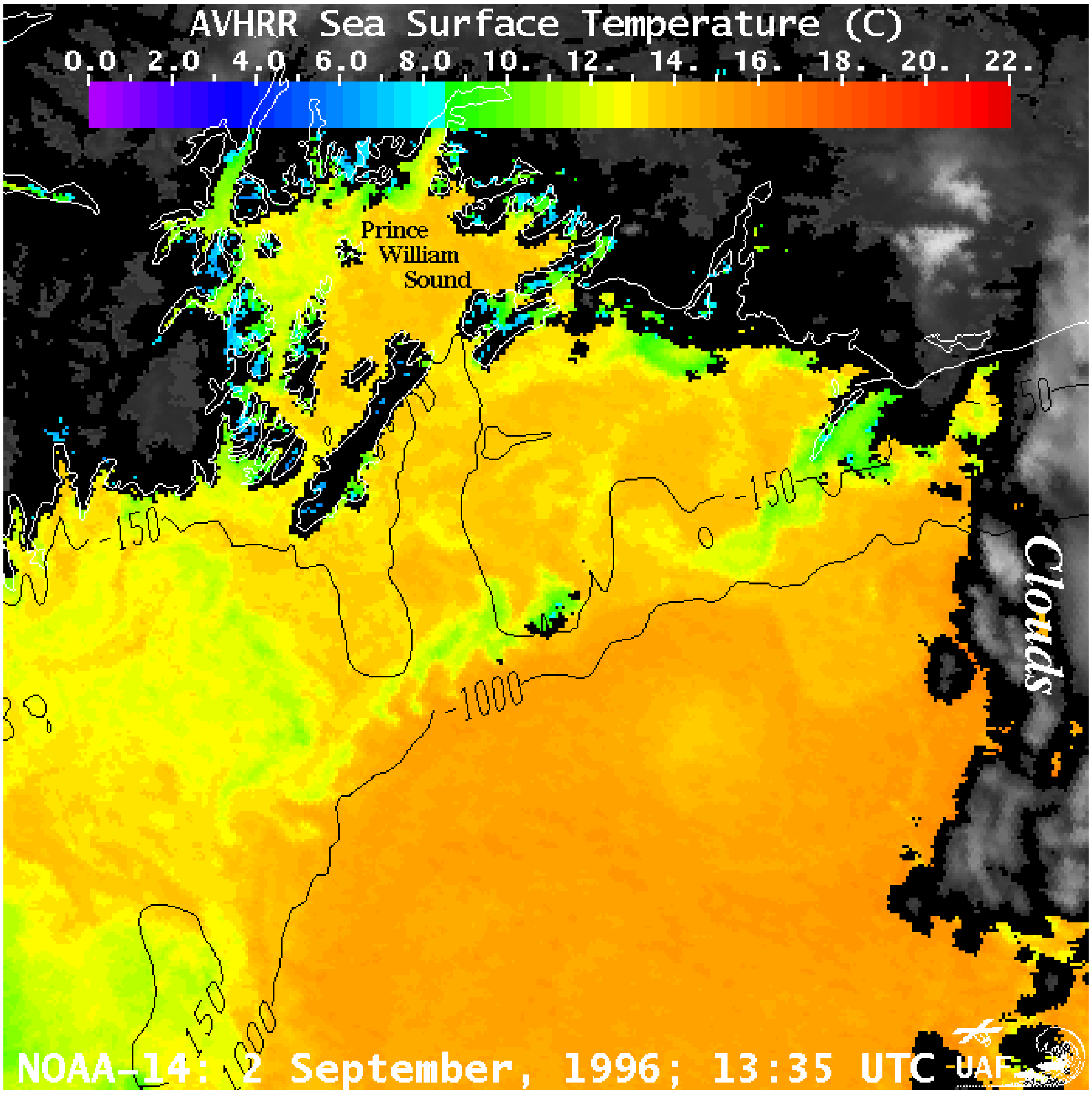


Figure 14. Advanced Very High Resolution Radiometer image of sea surface temperature for 2 September 1996 for Prince William Sound, AK and the continental shelf and offshore regions outside Prince William Sound, AK. The 150 m and 1000 m depth contours are shown. (Figure courtesy of Dr. David Eslinger, Institute of Marine Science, University of Alaska, Fairbanks)

coast of the region in the ACC can be complex and introduce water and organisms from the outer shelf (and perhaps further offshore) into inner shelf regions and fjords like PWS.

Although the focus of the study is on the higher trophic levels (pink salmon; the zooplankton upon which they feed; and, predators and competitors of the juvenile salmon), observations during the process studies should include nutrient 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 (like the CCS).

Studies of the CGOA will use many of the same methods required (and described earlier) for studying the CCS ecosystem (e.g, moorings, ships, drifters, remote sensing, surveys, etc.). Rather than repeat those details here, we describe some specific types of studies that should be conducted during Year 4:

- broad-scale surveys of the environment—SEASOAR or similar technology should be used to provide the physical context and map some biological parameters (e.g., fluorescence, multiple frequency acoustics, and optics) for a region encompassing ca. 150 km cross-shelf and 300 km alongshore. Weather permitting, a SEASOAR survey of that region might require 7-10 days of shiptime. Hotspots (e.g., aggregations of fish; euphausiid swarms) in the acoustics or bio-optics should be sampled using conventional (e.g., MOCNESS) nets to provide specific information on the prey field. Acoustics (supplemented by appropriate in situ collections [e.g., trawling, seining]) should be used to measure the abundance of pink salmon and other fish species, and net sampling will be needed to collect biological specimens for diet studies and to estimate growth rates [see next two bullets].

- diet of juvenile salmonids and competitors and predators—These will consider differences in the availability of different prey types, and the effects of mesoscale variability.

- determine growth rates of juvenile salmon during their residence in the coastal environment—Growth can be evaluated from marked fish using scales or otoliths; condition of the fish should be evaluated.

Juvenile salmonid habitat utilization and diet and growth rates should 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 each cruise. Finally, a second Eulerian survey would be conducted of the entire region at the end of each cruise.

Ideally, this sampling 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, but especially juvenile pink salmon, 4) growth rates of juvenile salmon during their residence in the coastal environment, and 5) the physical environment. Additionally, some information will be learned in this year about the dominant sources of juvenile salmon mortality, but the intensive studies of predator abundances, distributions, and foraging rates will be the

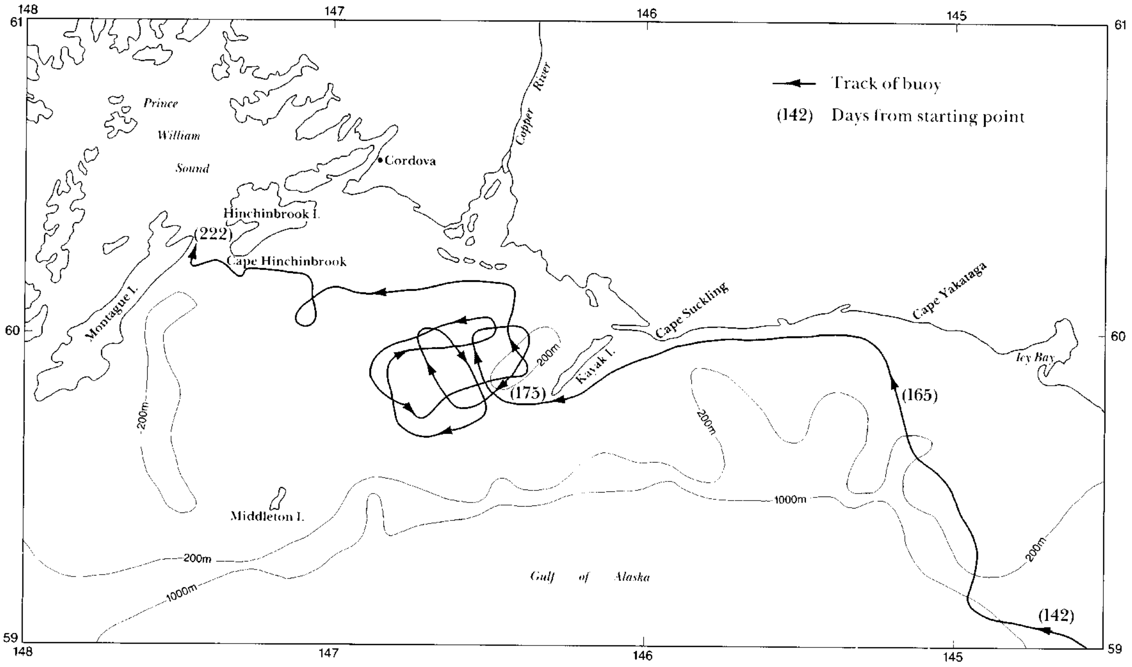


Figure 15. Trajectory of satellite-tracked drifting buoy released in the Gulf of Alaska in summer 1976. Note the generally along-coast flow east of Kayak Island, the eddy west of Kayak Island, and the movement of the drifter across the shelf and into Prince William Sound. (from OCSEAP Staff 1986).

primary focus of the CGOA studies in Year 6 (see paragraphs below). Process studies in both years should be coordinated with estimates of return rates (survival) of hatchery released fish (obtained from the hatchery, and fishery collections of thermally tagged fish), and with estimates of growth determined from analysis of scales and/or otoliths from returning or fishery captured fish. 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 other salmon species to have survival or growth rates impacted by interannual or interdecadal variability in coastal conditions.

Year 6 studies in the CGOA will focus specifically on documenting the sources and rates of juvenile pink salmon predation mortality. In addition to the types of observations described above for Year 4 studies of the CGOA, the following should be emphasized in Year 6 studies:

- identify and estimate abundance of predators on juvenile salmon; this would include other fishes, birds and mammals. This may require directed studies encompassing a larger region, perhaps including the Shelikof Strait, than some of the broad-scale surveys done in Year 4.

- determine the predation rate of various predators on the juvenile salmon

The focus of process studies in Year 6 will be to determine mortality of juvenile pink salmon as they transit the coastal zone from the vicinity of PWS until they depart the shelf for deep water. This period, along with the period spent in PWS, is thought to be the time when overall year-class strength is determined. Mortality of the juvenile salmon during this period is likely due to predation, and thus is sensitive to the number, distribution, and feeding rates of salmonid predators. Since it is not known how far to the west the pink salmon emigrating from PWS reside on the shelf in the Alaska Coastal Current before moving further offshore, we recommend that the sampling surveys for the migrating juveniles (and their predators) extend further to the west—into the Shelikof Strait—than the process studies proposed for Year 4. Information on the juvenile pink's residence time in the shelf environment, and their migration pathway to the deep ocean is very important because predator (esp. adult pollock and bird) abundances in the Shelikof Strait region, north and west of Kodiak Island, are significantly higher than they are on the shelf region outside of Kodiak Island and PWS. If the juvenile salmon pass through Shelikof Strait, depending on the time of the year, mortality from pollock predation may be very high. Some spatial and temporal resolution within the sampled area will be sacrificed to sample over a larger region in Year 6.

U.S. GLOBEC studies in this year must be coupled/coordinated with the shelf-wide trawling surveys for salmonids of the Ocean Carrying Capacity program and the NMFS acoustic surveys of adult pollock. The goal of the U.S. GLOBEC process studies in Year 6 will be to track the thermally-tagged hatchery released juvenile pink salmon as they are advected (and/or migrate) westward and southward, passing either south of Kodiak Island or through the Shelikof Strait, until they leave the shelf and enter deep water. Along this trajectory observations and sampling of suspected salmon predators will be done to estimate the sources and rates of natural mortality of the advected/migrating salmon cohort. The rate of natural mortality is not constant for all ages within the salmon cohort, and will vary both spatially and temporally as predator abundances vary. Mortality rates of marine fish are usually highest in early life (as larvae and juveniles), and decrease with growth, prior to final spawning and senescence. Predation by a variety of species (fishes, mammals and birds) is the most frequent cause of natural mortality in most marine fishes. Identifying the dominant predators, their distributions, which are probably patchy, determined somewhat by oceanographic conditions, and quantifying predation rates are given high priority in this year. Predator distributions, abundances and temporal phasing to prey populations may respond to interannual and longer-term variations in ocean conditions.

Synthesis

Synthesis includes a number of activities. Some will occur throughout the Northeast Pacific program, others will necessarily be more concentrated during the final years of the program. This is reflected in the effort devoted to synthesis in the timeline. There are numerous, at present mostly disconnected, research, monitoring, retrospective and modeling efforts ongoing or planned along the west coast of North America. In addition to U.S. GLOBEC, other large programs are 1) the CalCOFI long-term studies of the California Bight region to just north of Point Conception, 2) the NOAA-COP sponsored programs along the west coast (two in particular are relevant--the SEBSCC (Bering Sea) and PNCERS (Pacific Northwest Coastal Ecosystem Regional Study)), 3) the Exxon Valdez Oil Spill Trustee Sound Ecosystem Assessment (SEA) program, 4) NOAA/NPAFC Ocean Carrying Capacity (OCC) program, 5) NOAA's FOCI investigations in the Shelikof Straits, 6) the Canadian funded study of the La Parouse ecosystem, 7) Canada GLOBEC research, 8) NOAA's triennial groundfish survey along the U.S. west coast, and 9) NOAA's mammal surveys conducted every 4-5 years. There are also numerous individual investigator studies of various west coast ecosystems that are related to U.S. GLOBEC studies in the Northeast Pacific. Some of these are the GAK1 monitoring line off Seward Alaska; the Line-P sampling done by the Intitute of Ocean Sciences, Sydney, BC; intermittent sampling programs that have been conducted off of a) Newport, OR, b) Point Reyes, CA, c) Monterey Bay, CA; and others unknown. U.S. GLOBEC recognizes the need to foster intercommunication and coordination among these programs and individual investigator projects, to provide the larger picture of climate change impacts on Northeast Pacific ecosystems. This synthesis activity should begin immediately.

During the final years of the Northeast Pacific program timeline, synthesis includes completing the analysis of the samples collected during the Northeast Pacific GLOBEC program. It also includes deriving new understanding from those studies, and especially from the activities that couple the monitoring and research activities with the retrospective and modeling efforts. Most importantly, this synthesis will use the results of U.S. GLOBEC's research endeavours in the downwelling CGOA and upwelling CCS to consider how marine populations (esp. zooplankton and salmon) residing in the nearshore regions of these two, contrasting, coastal ecosystem types differ in their responses to physical forcing, including forcing due to large-scale climate. During recent years, catches of salmon from Alaskan and northern British Columbia waters have been at historic highs; conversely, catches of coho and chinook salmon from Washington, Oregon and California have been so low that some of the fisheries have been closed to commercial harvest. U.S. GLOBEC's scientific interests in the nearshore ecosystems of the west coast of North America, coupled with the regional interest in salmon, economically and socially, demand that U.S. GLOBEC undertake an integrated research approach in the Northeast Pacific that encompasses both the upwelling and downwelling regions.

A final activity that falls within the realm of synthesis is to conduct comparative studies of the results of the Northeast Pacific program (in the CGOA and CCS) with those obtained from the U.S. GLOBEC funded studies in the Northwest Atlantic. Specifically, U.S. GLOBEC desires more than the development of scientifically strong and socially relevant regional programs—the U.S. GLOBEC program, in the broadest sense, should provide an opportunity to obtain a broader understanding of the processes structuring marine ecosystems. One way in which this may be accomplished is by encouraging explicit comparisons across U.S. GLOBEC regional studies. These comparisons could be accomplished by focusing on physical processes (transport, residence time, frontal dynamics might be examples) or biological processes (zooplankton production, etc.). Alternatively, related taxa in different U.S. GLOBEC study regions might provide a framework that could lead to more general insights. For example, are there broader understandings that can be obtained by comparing how large calanoids (*Calanus* in the NW Atlantic; *Calanus* and *Neocalanus* in the NE Pacific) and perhaps, gadids (cod and haddock in the NW Atlantic; pollock in the CGOA), respond to physical forcing and food-web relations in different regional ecosystems, that might not emerge from a single regional study alone?

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