# U.S. GLOBEC

## *Global Ocean Ecosystems Dynamics*

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

## *Eastern Boundary Current Program*

## *Report on Climate Change and the California Current Ecosystem*

*Report Number 7*

*September 1992*

This is a report of the GLOBEC workshop on eastern boundary currents and climate change with focus on a field program on the California Current ecosystem. The workshop was held at Bodega Marine Laboratory of the University of California on September 17-20, 1991. The organizing committee for the meeting was: John Hunter, David Mackas, Dennis Hedgecock, and Ted Strub.

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# EXECUTIVE SUMMARY

## Rationale for a U.S. GLOBEC Field Program in the California Current System

It is no longer reasonable to assume that marine populations live in a stable environment. Both paleo-oceanographic and contemporary data indicate strongly that the circulation and average physical properties of the coupled atmosphere-ocean system change at time scales ranging from interannual to millennial. Some of this variability is natural; some may be caused or amplified by human activities. In either case, it is important to know how marine ecosystems will respond. GLOBEC (Global Ocean Ecosystems Dynamics) is the component of the U.S. Global Change Research Initiative that will address these issues.

Research sponsored by GLOBEC will have several shared approaches and themes (U.S. GLOBEC Initial Science Plan, Peterson et al. 1991). The key elements include a close working partnership between physicists and biologists, process-oriented emphasis on the linkages between physical and biological components of the ecosystem, field programs combining observation with numerical modeling, and advanced data collection technologies.

Eastern boundary current "upwelling" ecosystems have been identified as important study areas by both national and international GLOBEC planning committees. To develop the next stage of GLOBEC research on these systems, 54 participants of the U.S. GLOBEC workshop on eastern boundary current ecosystems met from September 17 to 20, 1991, at the Bodega Marine Laboratory of the University of California. The workshop was jointly sponsored by the National Oceanic and Atmospheric Administration (NOAA) and the National Science Foundation (NSF). Its goals were to identify and discuss key scientific issues associated with GLOBEC field research on eastern boundary current ecosystems in general, and on the system bordering the west coast of North America (the California Current) in particular.

## Workshop Structure

The workshop began with background briefings on GLOBEC planning and research activities (by U.S. GLOBEC steering committee and NSF representatives); an overview of recent and coming physical oceanographic research in the California Current system, and the capabilities of and probable time window for coming satellite missions (both by P.T. Strub); and recent and planned NOAA/NMFS research programs (by P. Smith).

Participants then separated into nine multidisciplinary working groups. Most of these groups dealt with a subset (often scale-dependent) of climate-population or biological-physical linkages believed to be particularly important and appropriate for study in the California Current. Some of these linkages had already been identified by the U. S . GLOBEC steering committee (e.g., transport and retention of organisms by mesoscale hydrographic features; latitudinal gradients; seasonal and interannual time scales). Others (e.g., the potential for abrupt change in composition and structure of biological communities) were identified through discussions between the workshop cochairs and potential workshop participants. An additional set of working groups dealt with the opportunities and requirements of particular kinds of information (acoustic and optical sensors, biotechnology, and the local paleo-oceanographic record). For each topic, working groups were asked to prepare a report identifying key research questions, optimal species, study sites, tools, and observation periods. At the end of each day, a plenary session reconvened for brief summaries of recommendations from each working group.

## Working Group Reports

The individual working group reports are summarized here and presented in detail in Section 3. The final part of this Executive Summary is a brief discussion of some important additional or shared themes that emerged in discussions within and between working groups.

### 1. Latitudinal Gradients Within the Eastern Boundary Current System

The California Current spans more than 20° of latitude along the west coast of North America. Its range exceeds the scales of dominant atmospheric pressure systems and of regional coastal morphology. From north to south it can be divided into three major regions, each differing from the others in wind stress, intensity of coastal upwelling, coastal morphology, freshwater inflow, and influence of long-time-scale advection. The working group recommends that the overall field program include a between-region intercomparison of physical forcing and biological response. The borders of these regions appear to be zoogeographic boundaries for some species, population boundaries for others. Still other species migrate through all three regions, but occur in each at different life stages. As noted above, a variety of physical processes contribute to the regional differences. The existence of latitudinal gradients provides a "natural experiment" on the relative importance and role of different forcing functions in marine population dynamics. As well, the spatial gradients of the physical processes are not fixed, but shift during the El Niño/Southern Oscillation, intrusions of subarctic water, and other events. It is highly plausible that they would also shift under changing global climate, but by no means certain that the shifts would be of uniform magnitude and direction.

### 2. Importance of Mesoscale Physical Features to Ecological Processes in the California Current System

Oceanographers have long known that the physical and biological characteristics of eastern boundary current ecosystems vary intensely in space, but until very recently there have been no observational tools for resolving the pattern of this variance. Satellite observations of surface temperature fields in eastern boundary current systems have revealed a complex and energetic system of filaments, squirts, and persistent eddies. Within the California Current system, these recurring mesoscale-to-subregional flow features are most prominent off the central and northern California coast. Both satellite (ocean color) and ship-based measurements show a strong spatial association between biological pattern and these physical structures. But the causes for the biological pattern (i.e., the importance of a particular class of physical feature for aggregation, growth, retention, and dispersion of a particular population or trophic level) remain poorly known. A null hypothesis is that shared physical and biological patterns result solely from shared advective history. The working group recommends research to test this as well as a number of alternate hypotheses. The research should include comparisons of population density, genetic composition, and demographic rates inside and outside major mesoscale flow features; measurement of advective loss from or delivery to core habitat; study of the intensification of environmental gradients by convergent secondary flow fields; and evaluation of the effect of resulting sharp environmental gradients on organisms that move into the gradient region. A number of technical needs were identified. Satellite observations and drifters are needed to direct biological sampling. Biochemical techniques are needed to evaluate population structure and demographic rates. Bioacoustic instrumentation is needed to resolve detailed spatial covariability of biomass and size distribution.

### 3. Paleo-oceanographic and Long-Term Historic Evidence of Past Variability

Two major challenges of the GLOBEC program are the detection of the ecosystem's response to global change, and the separation of anthropogenic effects from natural climatic variability. One of the most powerful tools for resolving these issues is time series analysis. The California Current system provides two exceptional and complementary sets of time series: the high-resolution paleosedimentary record, and the California Cooperative Oceanic Fisheries Investigations (CalCOFI) data set and sample archive. The working group recommends enhanced use and analysis of both. The anaerobic sediments of the Santa Barbara Basin and other localities retain detailed annual chronologies from which the dynamics of major fish populations, plankton, and climate variability can be reconstructed over hundreds of years by using animal and plant remains and geochemical techniques. The CalCOFI data document the behavior of the ecosystem over the last four decades and can be interrelated with the sedimentary record. Both can be linked to known changes in climate and ocean circulation. Both can also be used to evaluate the response of numerical models to simulated environmental change.

### 4. Nutrient Input Mechanisms in Eastern Boundary Current Regimes

Eastern boundary current ecosystems are among the most biologically productive. A range of physical processes collectively cause relatively high levels of new nutrients at the sea surface. New nutrient input and subsequent primary production (and the variability of these) can significantly affect upper trophic level productivity and community structure. The working group recommends study of the importance of 'bottom-up" control of eastern boundary current ecosystems in the following areas: role in setting large-scale average productivity and carrying capacity; correlation of local input rate with spatial and temporal variations in food quality; effects of food quantity and quality on consumer community structure; sensitivity of energy transfers between trophic levels to physical variables such as nutricline depth, upwelling rate and timing, and large-scale and mesoscale advective pattern.

### 5. El Niño/Southern Oscillation (ENSO) Effects Within the California Current System

El Niño represents an environmental extreme in the eastern boundary regions of the Pacific Ocean, and is a dominant component of environmental variability at interannual scales. There have been 43 strong-to-very-strong El Niño events, and many weaker ones, in the five centuries since written accounts of climate were first made in the Americas. Any study of eastern boundary currents of the Pacific extending for a decade or longer should therefore expect to encounter an El Niño event. The changes associated with El Niño conditions should not be interpreted as prototypes for the effects of generalized global warming, and it is not yet clear to what extent ENSO frequency and intensity would be affected by greenhouse warming. But at the least, El Niño represents an important additive component of environmental variation, and it must be sampled to understand ecosystem response to the expected range of environmental conditions. A well-developed and complete El Niño "contingency plan" should be designed into all GLOBEC field programs to insure adequate coverage.

## 6. Special Tools

### 6.1 Technological Needs for Eastern Boundary Current Experiments

The working group strongly supports the recommendations of past U.S. GLOBEC reports on the acoustical and optical needs (Holliday et al. l991) and biotechnology needs (Incze and Walsh 1991) of GLOBEC field programs. The group stresses that developments proposed in these reports and subsequently described in requests for proposals are vital to eastern boundary current programs as well as to other GLOBEC field programs. A few new technological needs specific to eastern boundary currents were identified, including biochemical techniques that can be applied to small amounts of sediments and archived plankton collections, and special tools for collecting sediment samples. Instrumentation needs not met by current development projects were also listed.

### 6.2 The Role of Models in the Study of Eastern Boundary Current Systems

A suite of eastern boundary current ecosystem models is needed to further our understanding of the California Current ecosystem. The working group recommends that development and sensitivity testing of such models begin immediately. For generality, the structure should allow alternate models of component processes to be tested. Because of the complexity of the system, the biological component of the model should include multiple trophic levels, each containing several taxonomic and developmental-stage subdivisions. Other model components requiring considerable research and development include the physical model, patch dynamics, migration patterns, and reproductive patterns. The long-term goal is a set of models that reproduce the behavior of the natural system, including the response to climate change. But the initial objective should be to understand the dynamics of the system rather than to reproduce or predict detailed time series.

## 7. Linkage of Observation Programs at Different Time and Space Scales

Mechanistic understanding of individual physical-biological linkages within the California Current system will require a number of intensive and relatively localized and independent process studies. To understand the interrelationships among these processes and the ecosystem's overall response to environmental change, it will be necessary to link these intensive studies. It will also be important to sample oceanographic trends and events that occur outside the "intensive" observation window. The working group made a number of recommendations to accomplish these goals. Intensive studies should be undertaken for a total of 5-10 years; should include a basic suite of important taxa; and should resolve cross-shore domains (coastal, shelf, and offshore) within each of the three major alongshore regions identified by the working group discussing latitudinal gradients (section 3.1). Less-detailed monitoring should be maintained for about 20 years; should provide near-real-time output of basic data; and should be able to trigger opportunistic intensive studies of special conditions whenever they occur. Both intensive and monitoring studies should be timed and designed to take advantage of available satellite sensors. Data management and exchange protocols should be specified in advance. Finally, numerical models spanning multiple levels of system organization (e.g., individual, population, community, ecosystem) should be used to identify particularly important areas of information.

## 8. Major Shifts in Species Composition and Ecosystem Structure

Time series of physical and biological measurements in eastern boundary currents exhibit abrupt changes in component variables; these changes seem unpredictable and inconsistent with those of the preceding time period. Such qualitative shifts are obvious in long-term records of temperature and fish abundance, and may also be related to abrupt gradients in within-time-period spatial distributions. Most recently, a major shift occurred in the mid 1970s from a colder to warmer-than-average regime in the California Current. This shift was accompanied by a drop in zooplankton abundance, vigorous recovery of the depleted sardine population in the Southern California Bight, changes in salmon runs in British Columbia, and many other changes. Despite the recognition that physical and biological variables often exhibit nonstationary properties, this concept is overlooked in actual practice. For example, resource managers typically use constant reference points such as steady-state carrying capacity and equilibrium-unexploited abundance in their models. Steady-state assumptions are clearly inappropriate even in the absence of anthropogenically forced climate change because qualitative shifts are a normal property of eastern boundary ecosystems. Thus, the group hypothesizes that the ecosystem response to global climate change may consist of abrupt changes in qualitative states - step functions rather than gradual trends paralleling the increasing atmospheric concentration of greenhouse gases. As part of the eastern boundary current GLOBEC program, the working group strongly recommends research on qualitative shifts, including the physical-biological linkages causing and maintaining shifts, the role of system nonlinearities, evaluation of sensitivity to initial conditions, and prediction or early identification of abrupt change. Understanding the mechanism of long-term qualitative change in eastern boundary current ecosystems will be a major intellectual challenge. Even if prediction proves unfeasible, early recognition of qualitative shifts would be beneficial. Therefore, a major goal of this proposed GLOBEC research is to develop a diagnostic capability that could be implemented by a line agency such as NOAA.

## Shared and Emergent Themes

Three concepts frequently recurred in working and planning sessions and deserve to be highlighted as unifying themes for the entire workshop.

The first of these themes was a keen interest in abrupt changes in species composition as a characteristic of eastern boundary current ecosystems and as a response to climate variability. For fish, major qualitative shifts in the pelagic community have been documented by both historic catch data and the paleosedimentary record. For plankton communities, major changes in composition have been observed both in spatial structure and in multiyear time series. There are several reasons why qualitative change is an important concern . The first is theoretical evidence that complex systems may have multiple quasi-stable states. Each state, once established, may resist moderate levels of perturbation, but once disrupted may be very slow (or even unlikely) to reestablish itself. A second reason is that most resource management models assume gradual approach to global equilibrium and are poorly equipped to predict or reverse rapid exogenous change. A third reason is that many consumer species (including people) are highly specialized in their prey preference. A major qualitative change at one trophic level may therefore transfer broadly through the ecosystem.

The second theme is a broad-brush but highly suggestive correspondence between the boundaries of biological and physical domains. Although further research is needed, there is evidence for shared boundaries in both large-scale and mesoscale spatial pattern, and in the distributions of planktonic, nektonic, and benthic species. Despite the large latitudinal range of many species, the California Current encompasses an extremely rich large-scale mosaic of life-history strategies. This is particularly evident in the spatial and seasonal allocation of reproductive effort. There is also a mosaic of physical forcing that is particularly pronounced for flow-field variables. This suggests a useful reinterpretation of "endemic" distributions: instead of being adapted to the local scalar environment (e.g., a water mass), species or populations may be primarily adapted to a prevailing local set of physical dynamics (presence or absence of seasonal flow reversal, presence or absence of coastal buoyancy input, seasonality and intensity of upwelling, seasonality and intensity of jets and eddies...). This can be viewed as an extension of the "member-vagrant hypothesis" (Sinclair 1988). A key point is that core habitat is defined by the intersection of a set of flow-field characteristics; the individual components of this set may be affected very differently by changes in large-scale climate . Research should examine the importance of different physical components, their potential for spatial and timing shifts, and the plasticity of organisms' adaptive response.

A third shared theme was an emphasis on the flow-through character of eastern boundary current systems. There is substantial spatial propagation and advective throughput of water properties, physical features, and organisms. In consequence, research programs will usually need to look "upstream" for causes and precursors of local conditions; thus they will need to cover large areas.

In addition to the three shared concepts, a consensus existed on three methodological issues or approaches. First, a consensus existed on the taxa that would be the primary focus of the program. These include euphausiids, copepods, and thaliaceans among the zooplankton; hake, anchovy, and sardine among the finfish; and crab, barnacles, and urchins among the meroplanktonic benthos. These groups account for much of the total animal biomass in the various domains of the system, and include a broad range of life strategies. However, the list is not intended to be restrictive; there will be many questions for which other or additional taxa should be studied.

Secondly, there was agreement on the need for satellite oceanography to provide a spatially detailed overview of the California Current. The measurements of particular interest are temperature, ocean color, and sea-surface elevation. Based on present mission schedules, satellite coverage of the system will be optimal for a period of about five years in the mid to late 1990s. This provides a strong incentive to begin the intensive field program soon.

Thirdly, there was general agreement that the program should take advantage of the unique time series data provided by the analysis of the sedimentary record of anaerobic basins, and CalCOFI and other archived data and samples. Such studies could provide the needed temporal linkages between proposed short-term site-intensive studies and the longer-term dynamics associated with climate change.

# 1 GOALS AND STRATEGIES OF GLOBEC

## 1.1 What Is GLOBEC?

GLOBEC (Global Ocean Ecosystems Dynamics) is a component of the U.S. Global Change Research Program. The biogeochemical and physical environment of the earth is in a state of flux, and the consequences of changes to our planet's climate and biological systems need to be identified. The goal of GLOBEC is to identify and evaluate how a changing physical environment will affect marine animal populations. The components of the program include:

1. A mechanistic approach with major emphasis on how the local environment affects the feeding, growth, reproduction, and survival of organisms;

2. A close working partnership between physical and biological oceanographers, featuring joint focus on particular sites and processes plus well-matched space and time scales;

3. Exchange of information about coupled physical-biological models and field observations and experiments;

4. Development and use of new technologies to reduce the problem of chronic undersampling of the sea (especially for biological variables).

## 1.2 Planning of U.S. GLOBEC Research

GLOBEC planning is under the leadership of a 16-member scientific steering committee initially appointed in early 1989. A master GLOBEC Initial Science Plan (Peterson 1991) and GLOBEC workshop reports have been published on modeling (Hofmann et al. 1991), use of biotechnology (Incze and Walsh l991), use of acoustical and optical technology (Holliday et al. 1991), and for a field study in the northwest Atlantic (Huntley and Olson l991). Each of the reports derives from planning workshops representing a broad sampling of the scientific community. The standard U.S. GLOBEC planning and implementation sequence is:

1. Identification by the steering committee of a major research need or study area.

2. A planning workshop with broad participation of the scientific community. The output of the workshop is a report listing the most appropriate and potentially rewarding research topics, tools, and approaches, and the terms of reference for all subsequent activities. (This report is the product of one such workshop).

3. A call for specific research proposals by NSF and NOAA, overlapping with
4. Detailed planning meetings among small groups of selected investigators and invited experts to determine the levels of vessel use, collect background data, and establish procedures for archiving and exchanging data.

5. Preparation and submission of competitive research proposals by groups of investigators.

6. Funding and execution of individual research projects.

## 1.3 Strategy for GLOBEC Field Programs

The U.S. GLOBEC Initial Science Plan identifies three major areas of scientific effort: theory and mathematical modeling; technology development; and multidisciplinary seagoing and laboratory measurement programs. Individual research projects are encouraged and supported not only on for their merit, but also for how well they support and complement other GLOBEC research. In particular, GLOBEC study sites and field programs should meet the following criteria:

l. Climate change context: the research should deal with marine ecosystems' response to changing environmental conditions.

2. Focus on processes and mechanisms: the goal is mechanistic understanding, not simply statistical forecasting.

3. Modeling component: the improvement of our capability to predict, which is an ultimate aim of GLOBEC, presumes a significant emphasis on modeling.

4. New technology: the research should adapt and exploit new technology to resolve the structure of populations and physical environment.

5. Multispecies focus: the research should include a variety of taxa (holozooplankton, fish, and benthos) so that the study of ecosystem response can be vertically integrated.

6. Definable populations: the populations under study should be demographically and geographically identifiable.

7. Population dynamics: research may focus on a variety of processes that do not expressly operate at the temporal/spatial scales of the population, but such studies must be complemented by concurrent research that establishes the importance of these processes to population dynamics.

8. Historical data base: study sites should have a considerable historical data base covering the distribution and abundance of target species, their physiology and ecology, local climate, and fluid dynamics at multiple scales. Historical data will be helpful not only in planning research, but also in model verification.

9. Broad scientific participation and application of results: to be achieved in part through integration with other global change programs, multiple agency support, and international collaboration.

10. Generality of system, both physical and biological: specific sites should represent major classes of marine ecosystems.

To date, three "large marine ecosystems" have been identified for early U.S. GLOBEC field effort (the Northwest Atlantic continental shelf and slope, the California Current system, and the Southern Ocean in the vicinity of the Antarctic Peninsula). All meet the above criteria, and complement each other by covering a broad range of ecosystem types and physical-biological linkages. The objective of this report is to outline the background for a basic research plan for the California Current ecosystem.

# 2 THE CALIFORNIA CURRENT SYSTEM

## 2.1 Rationale for a GLOBEC Eastern Boundary Current/Upwelling Ecosystem Program in the California Current

Several features of eastern boundary current ecosystems make them attractive as GLOBEC study sites.

First, they are quantitatively significant both to human populations and in the global biogeochemical balance. Many of the world's most productive fisheries are found in and near coastal upwelling regions. Particularly for developing nations next to them, these ecosystems have great economic and sociologic importance, and their demonstrated and potential biotic variability is a major concern. In the United States, the California Current borders a concentrated and environmentally conscious human population. This group places considerable aesthetic and moral value on understanding and preserving the health of the local marine environment.

Second, eastern boundary currents are oceanographically and ecologically distinctive. The dominant patterns of life history and energy transfer contrast with those of continental shelf ecosystems. For example, pelagic fishes achieve high biomass levels compared to demersal fishes. Flow fields and their effects on organisms are also distinctive. Mean wind stress is typically alongshore with large temporal variability. Surface-layer flow usually diverges from the coast. This divergence is often particularly intense in the vicinity of major headlands. Continental shelves are usually narrow, and large offshore bathymetric features are rare. Although current patterns show strong temporal and spatial patchiness with suggestions of recurrent structure, the currents are much less strongly steered by underlying bathymetry than in coastal systems with wide continental shelves. In consequence, geographically fixed and predictable opportunities for horizontal recirculation and retention may be rare and widely spaced. For planktonic and larval organisms, advective input and loss rates are thought to be large.

Third, eastern boundary current systems are particularly appropriate for examining the higher-frequency components of global climate variability. Biological and physical responses to forcing at interannual (e.g., ENSO events) to decadal time scales are known to be very strong. The local response almost certainly involves a variety of proximate physical coupling mechanisms (e.g., altered wind speed and direction, pycnocline depth, alongshore and cross-shore advection, buoyancy inputs). Important lower-frequency components of biological variability (decades to centuries) are also clearly evident in reconstructions from historical and sedimentary data.

Fourth, many of the dominant species extend over a broad latitudinal range and are exposed to large differences in the intensity and timing of seasonal circulation patterns. Particularly for the nearshore benthic community, strong spatial gradients in probability of successful recruitment appear to be linked to differences in upwelling intensity. There is clear potential for within-region comparative studies of the controlling mechanisms.

The historical knowledge base for portions of the California Current is excellent. This is one of the few oceanographic regions for which there is a long time series of archived plankton and larval fish samples (the CalCOFI program, 1949-date). Commercial catch statistics are available from the early part of this century. Sediments from anoxic basins provide a longer record of changes in relative abundance for major fish species. There have also been a number of major shorter-term studies of the physical and biological oceanography of this region. Recent examples include the Coastal Ocean Dynamics Experiment (CODE), the Northern California Coastal Circulation Study (NCCCS), Fronts cruises, and the Ocean Prediction Through Observation, Modeling and Analysis (OPTOMA) and Coastal Transition Zone (CTZ) programs.

## 2.2 Overview of the California Current System

The large-scale structure of the California Current System has been sampled "synoptically" by only a few of the early CalCOFI surveys, with very coarse sampling (Wyllie 1966; Hickey 1979). Our present understanding of that structure has been pieced together from smaller, regional studies, carried out at different times. Satellite images of surface temperature (SST) and color, such as Figs. l and 2, have added to our understanding of the large-scale structure of the California Current, although they only rarely indicate more than a fraction of the complete regime, due to cloud cover (Figs. 1 and 2 are rare exceptions). The field studies and satellite images reveal a rich structure of seasonal jets and eddies, superimposed on the slow, generally southward flow that is often shown as the typical eastern boundary current structure. In the future, altimeters will sample the surface velocity repeatedly over periods of 10 to 35 days, with spacing between tracks of 80 to 250 km. Geostrophic velocities calculated from the altimeter height fields should allow a more complete description of the time-varying surface velocity field.

In the north, off Washington and northern Oregon, the picture of the flow field was developed in the 1970s (Hickey 1979,1989; Huyer 1983). After the onset of southward winds in spring, upwelling raises isopycnals next to the coast, creating a density front and equatorward jet over the shelf. The front and jet move farther offshore in response to stronger southward winds, and return onshore when the wind relaxes or reverses. A subsurface, poleward undercurrent is usually found over the shelf break. During summer, the southward jet moves farther offshore (up to 100 km), and poleward nearshore countercurrents are often found.

Storms begin in fall, bringing northward winds that are strongest in this northern region. With their onset, the flow field becomes less organized, eddies are found offshore, and the northward Davidson Current develops over the shelf and slope. In the historical satellite data, filaments extending several hundred kilometers off this northwest region are found most often in fall. In both the upwelling and the storm-driven regimes, velocities in the jets and eddies can be energetic, reaching speeds greater than 0.5 m/s. The Columbia River creates a freshwater plume in the upper 5-30 m; the plume extends several hundred kilometers offshore to the southwest in summer and to the northwest in winter.

The flow field in the middle region between 35°N and 43°N has been the subject of intense study in the 1980s, with the most effort concentrated in the region between 37°N and 41°N. This is the location of the strongest southward summer winds (Nelson 1977; Strub et al. 1987). Field data from the CODE, OPTOMA, and CTZ programs show a strong seasonal cycle in the surface currents (Strub et al. 1991), with jets and eddies that are less energetic in winter than in summer, when velocities of over 1.0 m/s are observed (Kosro et al. 1991; Huyer et al. 1991) . Although neither the complete velocity structure nor the continuous evolution of even part of the structure has been directly observed, the evidence suggests that a nearshore jet develops after the onset of persistent southward winds in spring (perhaps similar to the jet and upwelling front found north of 43°N) and quickly moves offshore, developing meanders that extend 300 km or more from the coast. A poleward undercurrent is found over the shelf break and slope. Eddies are also found in association with the surface jet, often cyclonic inshore and anticyclonic offshore of the jet, although eddies of both signs have been observed both inshore and offshore of the jet. The eddies and meandering surface jet create the filaments seen in the satellite images of SST (Fig. 1) and color (Fig. 2). Multiple filaments are found in some cases, and the satellite imagery suggests that the flow field is more complex toward the south (34°N-39°N) than farther north. Poleward flow is often found next to the coast in late summer, especially during wind relaxations or reversals of the normally southward winds.

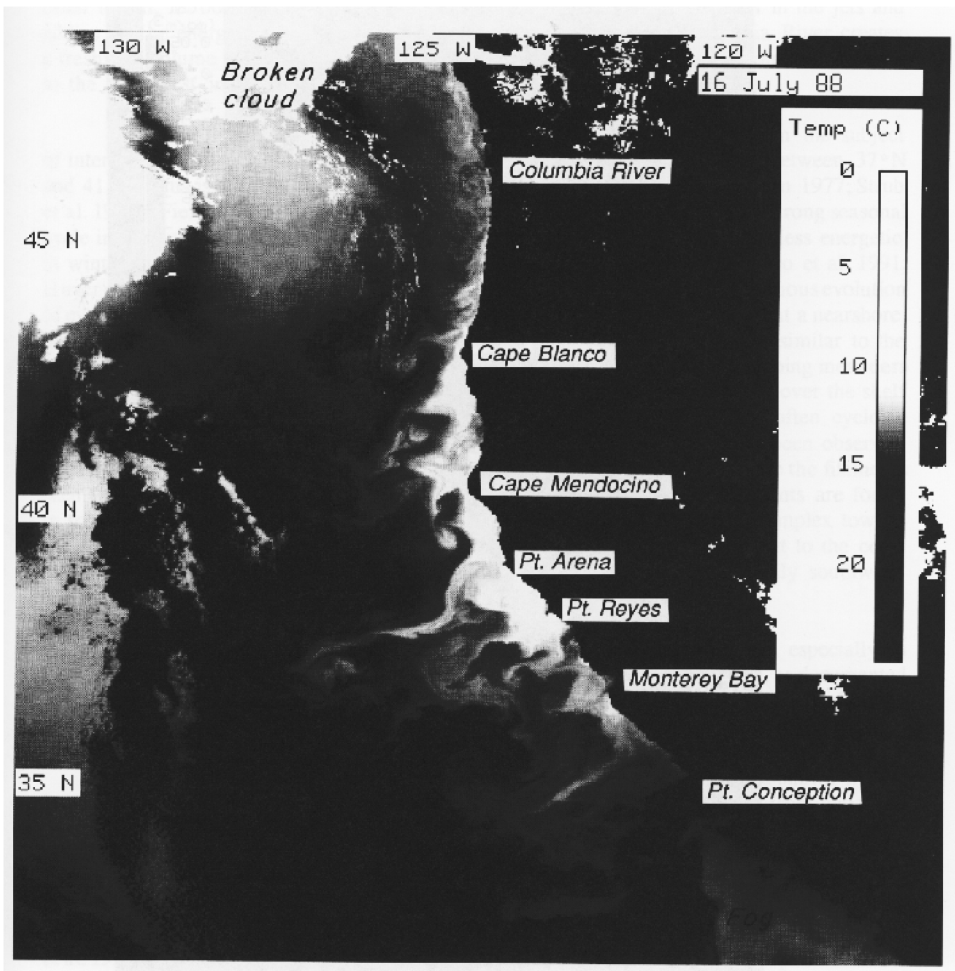


Figure 1. Surface temperature from the AVHRR satellite sensor on 16 July 1988 (from Strub et al. 1991)

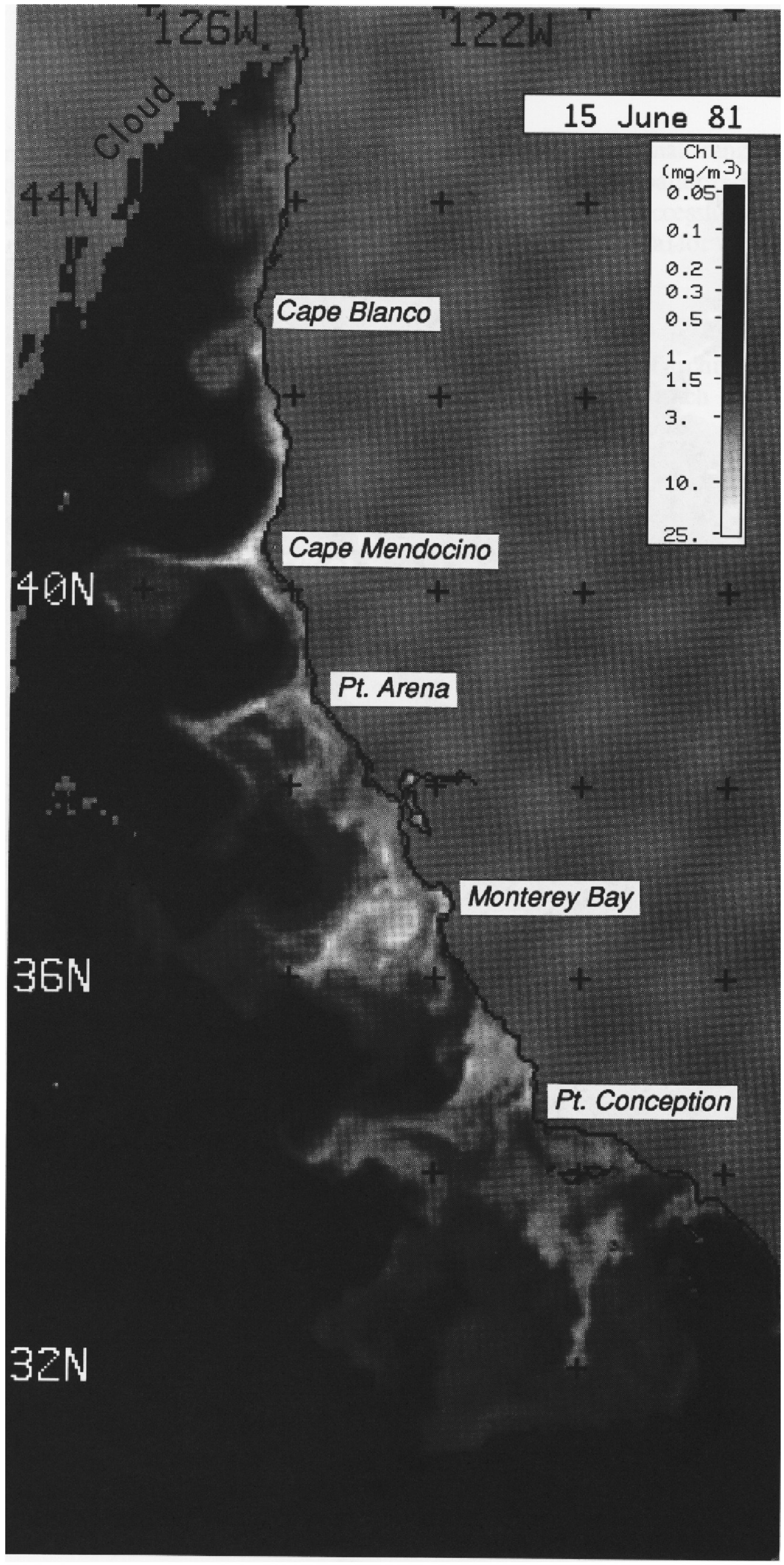


Figure 2. Surface chlorophyll content estimated from the Coastal Zone Color Scanner (CZCS) on 15 June 1981 (from Strub et al. 1991).

In the fall and winter, storms with northward winds affect the region, especially in the north. The northward Davidson Current develops next to the coast at this time, as documented in CalCOFI data for the region south of 370N (Chelton 1984; Lynn and Simpson 1987), although details of this evolving field are not well resolved by the coarse sampling.

An example of the large-scale flow structure found in mid-summer is shown in Fig. 3. The velocities in this figure were estimated by combining velocities derived from two types of satellite data. Most of the information comes from a sequence of six relatively clear AVHRR images of SST over a 30-hour period on 17-18 July 1988 (similar to the image in Fig. 1). Pairs of images, separated by 4-9 hours, were used to find velocities using the maximum cross-correlation (MCC) method of automated feature tracking (Emery et al. 1986). The average velocities at each location were found from the five fields formed from sequential pairs of images (Tokmakian et al. 1990). This average velocity field was then combined with cross-track geostrophic velocities from the ascending Geosat altimeter tracks from roughly the same period, using the method of objective analysis to fit a stream function to the data (Bretherton et al. 1976), to form the geostrophic velocities shown in the figure. A smoothing is inherent in the process, removing features with scales less than approximately 100 km.

Fig.3 shows a jet that appears near the coast in the north and separates from the coast in several locations. A meander off Cape Mendocino (40°N), with a cyclonic eddy inshore of the jet, similar to that shown by this figure (125.5°W), was sampled repeatedly in April-June 1987. The field sampling in 1988, at the time of this image sequence, covered the jet flowing to the southwest from Point Arena (39°N). This figure illustrates the highly advective nature of the California Current system, and is unlike the classic picture of the slow (0.1 m/s), gentle, mean flow in eastern boundary currents. An energetic jet (surface drifters moved at maximum velocities greater than 1.0m/s) flows continuously from 43°N to 35°N, extending hundreds of kilometers offshore and connecting to eddies that are up to 400-500 km offshore (129°W-130°W, 39°N-40°N) . Near-surface drifters that were deployed in the jet off Point Arena (39°N) in July 1988 showed that the cyclonic eddy at 37°N, 126°W-127°W and the anticyclonic eddy at 123°W-125°W, 35°N-36°N persisted for at least two months. Altimeter data indicate that the anticyclonic eddy farther offshore at 129°W-130°W, 39°N-40°N was present for at least two months prior to mid-July 1988 and may have propagated from a location closer to the coast, where an anticyclonic eddy appears in the altimeter field during February 1988.

The SST pattern from this July period in 1988 (Fig. l) resembles the patterns seen each July of 1981-87 (Strub et al. l991), indicating that this flow field is typical of summer, and suggesting that the location of specific features (the meander around Cape Mendocino, the jet off Point Arena, etc.) may be related to the capes or the subsurface topography, as suggested by laboratory and numerical models (Narimousa and Maxworthy 1989; Haidvogel et al. l991).

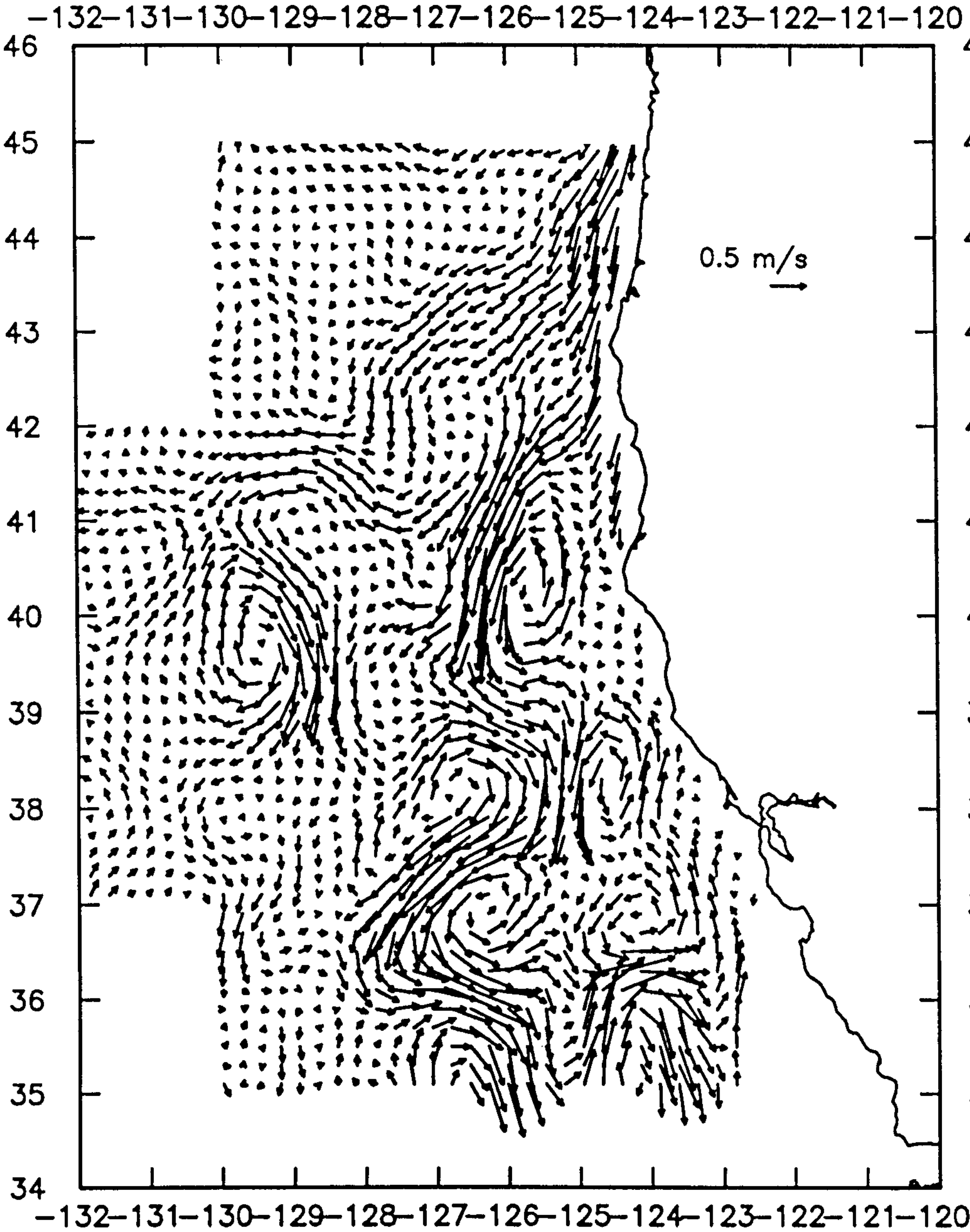


Figure 3. Surface velocity field estimated during mid July 1988 from a combination of altimeter cross-track geostrophic velocities and velocities estimated from a sequence of AVHRR images using automated feature-tracking (MCC). See Section 2.2 of text for details.

The relation of the meandering jet to water mass and biological properties is discussed in a number of papers that analyze the 1987 and 1988 CTZ data sets (Brink and Cowles l991) . A low tongue of salinity is found on the offshore flank of the jet at 125°W-127°W, 37°N-38°N in Fig. 3, consistent with its connection to regions farther north (Huyer et al. l991), where the Columbia River plume creates a shallow lens of very fresh water north of Cape Blanco (43°N). Zooplankton distributions also show that the core of the jet carries species not found locally on either side of the jet (Mackas et al. l991) . Nutrients and chlorophyll concentrations are high, and SST is low inshore of the jet (Hood et al. 1990, 1991; Kosro et al. 1991; Huyer et al. 1991; Chavez et al. 1991), although patches of high chlorophyll and narrow filaments of high nutrients and low temperature are sometimes carried by the core of the jet (Hood et al. 1991; Strub et al. l991).

Within the jet, regions of both local upwelling and downwelling are found (Kadko et al. 1991; Washburn et al. 1991; Strub et al. l991; Chavez et al. l991). Idealized quasi-geostrophic numerical models of the jet predict enhanced upwelling in the onshore-flowing branch and enhanced downwelling in the offshore-flowing branch of the meanders (Allen et al. 1991). Primitive equation numerical models with more realistic topography show a more patchy distribution of upwelling and downwelling, although they still seem to have more upwelling in the onshore-flowing branch and downwelling in the offshore-flowing branch. They also indicate greater convergence and downwelling on the northern edge of the offshore-flowing jet and greater divergence and upwelling on the southern edge of the jet (Haidvogel et al. l991; Hofmann et al. l991), consistent with the temperature-salinity structure found in detailed transects across the jet (Strub et al. 1991).

Thus several processes act to enhance productivity in the region within and inshore of the jet. The jet itself carries nutrients and phytoplankton along its inshore side, filling in the inshore region as it moves offshore. Local upwelling within the jet enriches it beyond the level caused by this advection. Cyclonic meanders and eddies inshore of the jet also raise isopycnals because of geostrophic adjustment, and bring nutrients into the euphotic zone, increasing productivity (Hayward and Mantyla 1990); anticyclonic meanders and eddies have the opposite effect. The net effect of the jet and eddy system on productivity, as indicated by chlorophyll pigment concentrations, can be seen in Fig.2, which shows the surface pigment concentration derived from the coastal zone color scanner (CZCS) satellite sensor on 15 June 1981. The SST pattern from the same day looks very similar, with low temperatures in place of the high pigment concentrations. Many of the features in this image are also similar to the SST pattern seen in the image shown in Fig. l. The distribution of high pigment concentrations is consistent with an enriched region within and inshore of a meandering jet, with detached eddies in the north, an elongated narrow meander off Cape Mendocino, an offshore jet at Point Arena, and a wider, more complex region south of Point Arena. More complete analyses of the multiyear CZCS data in the California Current system can be found in Thomas and Strub (1989, 1990), Strub et al. (1990), and Abbott and Barksdale (1991).

The region south of Point Conception ( <34°N) has been heavily sampled by the CalCOFI surveys. The average seasonal dynamic height fields from these data (Lynn and Simpson 1987) show the California Current to turn eastward, flowing into the Southern California Bight around 32°N, creating a cyclonic gyre within the bight that is strongest in late summer and fall. Direct measurements of currents over the shelf and slope north of

Point Conception show fairly persistent northward currents (in the face of persistent southward winds) with much less seasonality than found farther north (Strub et al. 1987; Chelton et al. 1988). The lower degree of seasonality off southern California is also found in the variance of Geosat altimeter heights along ascending tracks (White et al. 1990).

The biological effect of the flow into the bight can be seen in the summertime CZCS surface-pigment concentrations in Fig. 2. Oligotrophic water with low nutrient and pigment concentrations flows into the southern half of the bight, creating a strong front aligned east-west in the center of the bight(31°N-32°N), sometimes referred to as the Ensenada Front. This front is absent in winter, when the pigment levels are low everywhere, and is strongest in spring-summer and again in fall, after a brief disappearance in late summer (Thomas and Strub 1990). Farther south off Baja California, the pattern is more like that off northern California, with high pigment concentrations and low temperatures in upwelling regions near the major capes.

Physical and biological variability in the California Current system shows a strong relation to basinwide climatic variability on the interannual time scale, making it a good candidate for studies of longer-term climate change. During ENSO events, winds over the North Pacific change as a result of increased temperatures at the equator, resulting in a deeper Aleutian low as part of a pattern referred to as the Pacific North American (PNA) pattern (Horel and Wallace 1981). Warmer water at the equator due to global warming might produce similar changes in winds, affecting wind forcing over the California Current. The same change in basin-scale winds might displace the position of the zero of wind stress curl over the entire basin, which affects the latitude at which the West Wind Drift crosses the North Pacific. This would affect the flow into the California Current at the north and hence its transport, which has been shown to be related to zooplankton biomass (Chelton et al. 1982).

It has also been argued that global warming will increase the upwelling-favorable winds in the summer, by warming the land surfaces more than the ocean (Bakun 1990). Since eastern boundary currents contribute significantly to the amount of vertical carbon flux in the ocean, physical and biological changes in the current system might, in turn, affect the rate of climate change, providing a feedback mechanism of unknown sign. The CalCOFI data set and the sediment records from anoxic basins provide long time series with which to investigate the past behavior of the system, providing background for future studies. Finally, the strong latitudinal gradients in physical forcing within the California Current system provide a proxy for changing climatic conditions, transforming comparative spatial studies into hypothetical scenarios for climate change.

### 2.3 Characterizing the "Local" Environment for Marine Organisms

An organism's chances for successful feeding, growth, survival, and reproduction are set by its moment-to-moment responses to events in its immediate vicinity. However, changes in local environmental conditions and resulting changes of the ecosystem are not controlled solely (or even primarily) by local and small-scale physical events. Both depend upon components that are spread across the full range of oceanic time and space. The overall goal of GLOBEC data collection is to capture the variability to which the biological system is most sensitive, regardless of the space and time scales at which it occurs. For any single field program, the strategy is to identify and characterize the components of physical and biological variability and coupling mechanisms that dominate locally to control the environmental conditions experienced by the organisms.

A useful conceptual aid is to view the strength of biological response to oceanographic forcing as a two-dimensional (time and space) spectrum (Haury et al. 1978). In general, we want to concentrate effort on sites, species, and physical processes for which there are (1) pronounced maxima in this spectrum (strong physical/biological coupling) and (2) maxima that will be strongly affected by a changing global environment (in contrast to relatively fixed forcing such as that caused by tides).

In the California Current (and probably in most eastern boundary current systems) identifiable oceanographic "features" such as coastal promontories, eddies, jetlike currents and their frontal boundaries, and individual wind events are believed to play important roles in the overall physical and biological dynamics. In addition, variability at interannual time scales of 2-20 years appears to be important throughout the system (Chelton et al. 1982; Roesler and Chelton 1987), whereas variability at seasonal and upwelling-event time scales is important in at least the northern half of the region (Lynn and Simpson 1987; Hickey 1989; Strub et al. 1987, 1990). Because of progressive alongshore gradients in amplitude and seasonal phasing of the California Current system, it is also desirable to include large spatial-scale regional comparisons of forcing and adaptive strategy.

## 2.4 Satellite Coverage—1992-1999

The satellite sensors relevant to a California Current GLOBEC study are those that measure surface temperature (SST), color, surface current velocities, and winds (Fig. 4). Solar insolation might also be of interest and can be estimated from cloudiness via the same sensors that measure SST and color.

The AVHRR sensors carried on the NOAA polar orbiting satellites are presently the primary source of SST data. These measure infrared radiation (IR) in two or three bands, as well as near-IR and visible radiation, which are useful for daytime cloud detection. The use of two or more IR bands allows some correction for atmospheric absorption and scattering. Spatial resolution is approximately l km, and clouds limit the coverage. During periods when two operational satellites are up, it is possible to get four images per day at mid-latitudes, separated by 4-9 hours. Sequences of clear images can also be used to estimate surface velocity via several methods, allowing some estimate of horizontal heat transport, although these methods are still being developed and tested. At present, we expect that the series of polar orbiting satellites with AVHRR sensors will continue through the decade.

The next generation of geostationary satellites (GOES-NEXT) should be operational by the time a field program is carried out. These will have several IR channels and, because they sample every 30 minutes, may be useful in constructing composite maps of SST in regions where clouds are patchy. The spatial resolution will not be as fine as that from the AVHRR, probably in the 4-8-km range. The accuracy is expected to be comparable to the AVHRR, but will need to be tested. Resolution and accuracy at higher latitudes will not be as good.

Ocean temperature can also be sensed by passive microwave sensors, but the footprint of present sensors is too large (hundreds of kilometers) to be of much use in the California Current. Also, the land contaminates such microwave information for hundreds of kilometers offshore, further prohibiting the use of such sensors in this region.

Surface chlorophyll pigment concentrations are estimated from ocean-color sensors, from which estimates of phytoplankton biomass and primary productivity are also possible, although they are still in development. Clouds, fog, and mist interfere with color sensors, as they do with the IR sensors discussed above. Several ocean-color sensors are planned for the future, but the best sensor and only dedicated color mission presently planned and funded will be Sea-WiFS (Sea-Viewing Wide Field Sensor). It is scheduled for launch in the summer of 1993 and designed for a five-year mission. It will sample in eight visible bands, designed to estimate surface chlorophyll concentrations and to separately estimate dissolved organic matter, with approximately 1-km horizontal resolution and continuous onboard calibration. The SeaWiFS sensor will provide complete oceanic daytime coverage every two days (with large regions obscured by clouds), crossing the equator near noon. There are plans for a SeaWiFS follow-on in 1998, under EOS funding, to maintain continuous measurements.

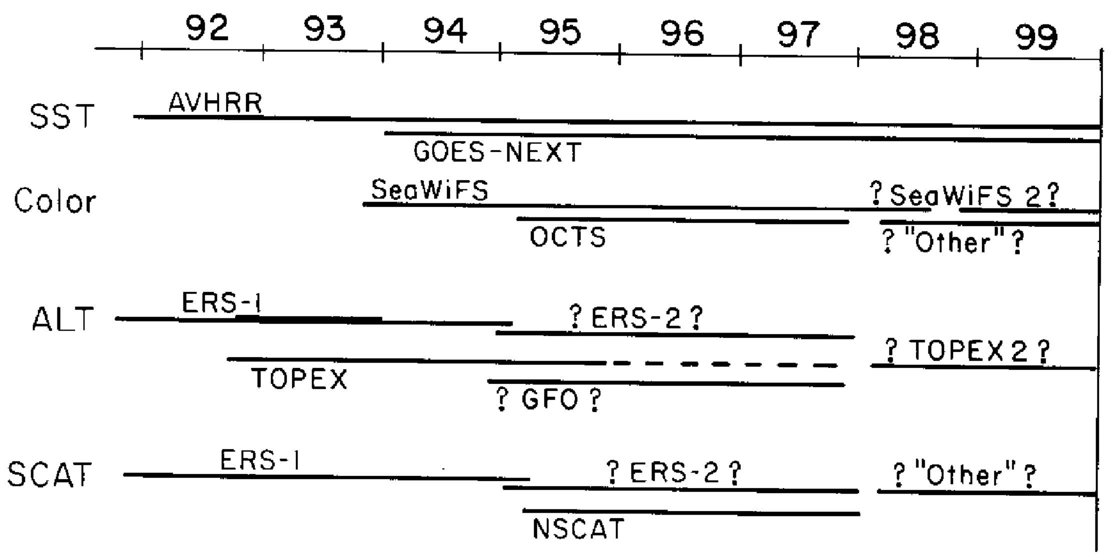


Figure 4. Time line of possible satellite sensor coverage through the 1990s.

Another instrument, the Japanese ocean color temperature sensor (OCTS), samples the same bands as Sea-WiFS, but with a poorer signal-to-noise ratio and an earlier-morning orbit, resulting in less accuracy. It will launch aboard the Japanese ADEOS satellite, which will also carry the U.S. NSCAT scatterometer, used to estimate the surface vector wind field (see below). The proposed launch date is early 1995, with a nominal three-year mission.

Other color sensors are planned by various groups for the period after 1998, but none are dedicated to ocean color. The oceanographic moderate-resolution imaging spectrometer (MODIS) sensor was designed with a tilting view angle to avoid sunglint (MODIS-T). Budgetary considerations have delayed it from the initial U.S. Earth Observing System payload. The nontilting version (MODIS-N) is still part of the payload. Data from MODIS-N, with a large number of visible, near-IR, and IR bands, will be similar to SeaWiFS, but with improved signal-to-noise characteristics and with the addition of bands to measure chlorophyll fluorescence. Because sunglint will contaminate part of the MODIS-N viewing area, two day global coverage will not be possible until both MODIS-N instruments are in orbit in the year 2000.

The European Space Agency (ESA) plans to launch the medium-resolution imaging spectrometer (MERIS) in 1998 as well. This is also a nontilting instrument. It is a full spectrometer, with 15 programmable bands (in terms of width and placement) that can be downloaded to the ground. MERIS will measure both ocean color and chlorophyll fluorescence wavelengths, in bands similar to MODIS-N but with poorer performance.

Surface geostrophic velocities can be calculated from the slopes of the ocean's surface heights, which are sampled along subsatellite tracks by altimeters. These instruments use microwave radar and are not affected by clouds. Altimeter data will be collected by the European remote sensing satellites, the first of which (ERS-1) was launched successfully in July 1991 with a three-year mission. The U.S. dedicated altimeter mission, TOPEX, will launch in the summer of 1992 with a nominal three-year mission, likely to be extended to five years. TOPEX will have an exact repeat track with a 10-day repeat, resulting in tracks separated by approximately 250 km. Along each track, cross-track geostrophic velocities can be calculated from the slope of the ocean height, but a long-term mean must be removed in order to remove the influence of the geoid, which is not known well enough to be removed in any other way. This also removes the mean velocity, leaving the time-variable signal (seasonal and shorter time scales). Although the ERS-1 satellite will change its orbit a number of times, it will be in an exact repeat orbit with a 35-day repeat period from April 1992 through December 1993.

Thus during mid 1992 through 1993, the combination of ERS-1 and TOPEX altimeters should sample the surface velocity field well enough to document the seasonal evolution of the jet and eddy system in the California Current. If TOPEX continues to function for five years and if an ERS-2 satellite is left in an exact repeat orbit during a year or more of the 1995-98 period, another high-resolution picture of the surface currents will be possible. It is also possible that a Geosat follow-on (GFO) may be launched by the U.S. during 1994, allowing similar overlap with TOPEX and good coverage of the surface velocity field in the 1994-98 period.

Winds are sampled by scatterometers, which are also active microwave instruments, unaffected by clouds. The ERS-1 scatterometer samples a 600-km band on one side of the satellite, covering most of the ocean in approximately three days. The footprint is approximately 50 km wide and cannot be used if any part of it touches land (no wind data from within 50 km of land). The scatterometer shares an antenna with the SAR instrument, therefore it is not operated at all times. The ERS-2 scatterometer will provide similar coverage beginning in 1995. Better coverage will be provided by the NASA scatterometer, which will be launched in early 1995 and will sample most of the ocean in approximately two days. The basic footprint of NSCAT is a 25-km region, although for most purposes it will be averaged into 50-km regions. Thus NSCAT may indicate winds on slightly smaller scales and closer to the coast than the ERS sensors. It is expected that wind fields from any given 2-day or 3-day period (from one sensor) will have relatively large errors (several m/s), but that averages of 10-30 days will be better.

For the above reasons, scatterometer winds will be less useful on time scales of 10 days and less (individual wind events, storms, etc.) and in the region within 50 km of land; they will be more useful for seasonal and interannual scales over the larger-scale California Current system. Measurements at buoys, and operational numerical weather prediction models will remain the primary source of wind data over short time scales and the only source of wind data within 25-50 km of the coast, except possibly for shore-based radar or lidar systems, which are still in the experimental stages. If the operational wind models assimilate the scatterometer winds into their forecasts, the accuracy of the forecast fields may improve significantly, providing a "dynamical interpolation" of the scatterometer winds on short time scales.

### 2.5 Linkages to Other Field Programs on North America's West Coast

The Office of Naval Research (ONR) initiative on Mesoscale Interactions of Weakly Nonlinear Regimes (hereafter called the EBC [eastern boundary current] initiative) will make field measurements off northern California during 1992-94. The field sampling will consist of a current-meter array extending offshore from August 1992 to August 1994. Ship surveys covering approximately 36°N-40N out to 128°W will be made twice in 1993 (spring and summer). Surface drifters will be deployed several times during the same two years; some of the drifters will carry spectroradiometers for bio-optical measurements. A meteorological buoy will also be deployed for one year at the offshore end of the current-meter array (450 km offshore), with additional sensors to measure the upper ocean temperature and velocity structure. The field surveys in the spring and summer of 1993 will include periods of more intense sampling in regions around eddies identified by the surveys and satellite images. NOAA (Fisheries) also plans to coordinate cruises looking at hydrography, zooplankton, and fisheries biology with the ONR surveys conducted during this period.

NOAA-Fisheries (La Jolla) proposes to carry out a west coast fishery hydrography program, FORAGE, which is designed to relate mesoscale features to survival and recruitment of groundfishes along the central California coast. The study area coincides with the ONR study area, and coordination of research activities with ONR is planned. FORAGE is proposed as part of the NOAA Coastal Oceans, Coastal Fisheries Ecosystem theme. Preliminary cruises are being made by NOAA scientists in support of FORAGE, and in coordination with ONR, but FORAGE is not funded by the Coastal Oceans Program at the present time.

Each year the CalCOFI program sponsors quarterly surveys of 16-20-day duration; six lines (68 stations) south of 35°N are occupied each quarter. The current sampling pattern has been used since 1985, and no plans exist to modify it in the foreseeable future. Although the pattern is smaller than in earlier years, the stations currently occupied each quarter have been consistently occupied for the last 40 years.

Canadian researchers have maintained time series sampling of biological and physical oceanographic conditions off the outer coast of Vancouver Island since 1985 (the La Perouse Program). Sampling lines extend about 100 km from the coast and (routinely) from the mouth of Juan de Fuca Strait to about midway along Vancouver Island. Additional lines to the north are occupied opportunistically. Current meters are moored at 3-4 locations; plankton samples (about 12 per survey) are collected during 5-6 surveys per year; and CTD profiles (about 50 per survey) are taken during about 10 surveys per year. Trawl and acoustic surveys of finfish distribution and stock size take place 2-3 times annually.

Other large-scale U.S. programs, such as the Joint Global Ocean Flux Study (JGOFS) and World Ocean Circulation Experiment (WOCE), are unlikely to contribute substantially to efforts in the California Current system. WOCE has solicited proposals for a mooring in the California Current system. At present, this mooring has a low priority and is not likely to be funded. WOCE line P17 extends offshore from the coast in the vicinity of the EBC survey region (38°N) and will be sampled once in mid 1993. This will provide a line of deep CTD casts to supplement the EBC surveys, which will usually sample only to approximately 200 m, since WOCE researchers use SEASOARs to make rapid, high-resolution surveys and will make only a few deeper CTD casts.

Field work carried out by other agencies and individual investigators from the institutions along the coasts of Mexico, California, Oregon, Washington, and Canada are difficult to inventory or predict with any certainty. Off Baja California, CICESE plans to sample offshore lines on a regular basis in what has been described as a "mini-CalCOFI." It will also equip two offshore islands with modern tide gauges, to estimate variations in transport in the 200 km next to the coast. Other continuing fieldwork includes studies supported by the Minerals Management Service in the Los Angeles Bight and investigations in Monterey Bay conducted by the Monterey Bay Aquarium Research Institute (MBARI); the University of California, Santa Cruz; Moss Landing Marine Laboratory, and the Naval Postgraduate School. NOAA-Fisheries, Tiburon Laboratory, conducts an annual survey for pelagic juvenile rockfish over the shelf off San Francisco, and every three years the Alaska Fisheries Science Center conducts a trawl survey along the shelf from the Canadian border to Point Conception.

Finally, an interdisciplinary group of coastal ocean scientists has joined together to form CoOP (Coastal Ocean Processes). The goal of this group, as stated in the Draft CoOP Science Plan (dated 11 February 1992), is "to obtain a new level of quantitative understanding of the processes that dominate the transports, transformations and fates of biologically, chemically and geologically important matter on the continental margins." The spatial domain of interest to this group extends from near shore to the continental shelf, slope, and rise.

Although still in its formative stages, the CoOP organization envisions field studies that would be initiated by a group of scientists who organize a workshop to define specific interdisciplinary objectives and the approaches needed to accomplish those objectives. In concert with the CoOP steering committee, the plan will be refined and distributed. Ultimately, proposals to accomplish the objectives would be solicited from the community at large. Since GLOBEC and CoOP share common interests in the transport and transformation of nutrients and biomass, those involved in the GLOBEC program should be aware of possibilities for synergism. As a hypothetical example, one could imagine a larger-scale GLOBEC program providing the spatial and temporal context for specific CoOP process studies with a focus over the shelf and/or nearshore zone.

## 2.6 International Linkages

We note in the preceding section that a possibility exists for linking existing U.S., Canadian, and Mexican field programs with a west coast GLOBEC field program. In addition, studies of the California Current raise the possibility for a number of international links to programs (possibly International GLOBEC) in other boundary currents. In eastern boundary currents off South America (the Peru Current system), northwest Africa (the Canary Current), and southwest Africa (the Benguela Current) wind-driven upwelling enriches the ocean and creates productive ecosystems. These current systems not only have similar environmental dynamics, but also are dominated, in terms of exploitable biomass, by very similar assemblages of pelagic fishes. Each system has substantial populations of anchovy, sardine, hake, horse mackerel, mackerel, and bonito. Bakun and Parrish (1982) make the case for comparative studies in eastern boundary current systems. They suggest that such comparative studies may reveal the environmental factors controlling reproductive success of these fishes. The same case could be made for studies of how marine populations of eastern boundary currents respond to climate change.

The Peru Current off central and southern Chile is potentially most similar to the California Current. The West Wind Drift in each hemisphere flows toward the east between 40 and 50 degrees and feeds into the equatorward surface current. A poleward undercurrent is often found over the shelf break in both systems. There is strong input of fresh water from the Columbia River (46°N) off North America and from heavy precipitation and coastal runoff south of 40°S off South America. The winds have a seasonal cycle which is greatest (including a reversal in alongshore direction) at latitudes of approximately 35°-40° in both systems. Satellite images show the presence of convoluted fronts in surface temperature and color, although the currents associated with those structures in the Peru Current have not yet been measured. Interannual variability has been shown to be strongly connected to ENSO events in the California Current, through both oceanic and atmospheric paths. This connection may be even stronger off South America, where the equator directly intersects the continent.

Eastern boundary current fishery recruitment studies on sardines and anchovy (SARP) have been proposed, and some work has been carried out under the Ocean Science in Relation to Living Resources (OSLR) Program of the Intergovernmental Oceanographic Commission (IOC) and the Food and Agriculture Organization (FAO). These studies did not progress to a point that would enable an extensive comparison of the systems, but they demonstrated that the comparative method was fruitful. SARP also provides a ready-made infrastructure for international GLOBEC to exploit and create a comparative eastern boundary current study.

In December of 1991, the North Pacific Marine Science Organization, PICES, held a workshop attended by scientific delegations from the United States, Canada, China, Russia, and Japan. One of the charges of the workshop was to identify key marine research problems and areas for cooperative research programs. Many of the PICES workshop recommendations are similar to those of the current GLOBEC report. For example, PICES recommended international studies of long-time-scale climate variability and species changes preserved in the varved sediments of the basins of the North Pacific, a recommendation of the current workshop. Clearly, an expansion of the work proposed here to an international boundary current program on climate change would be highly beneficial.

# 3 WORKING GROUP REPORTS

## 3.1 Latitudinal Gradients Within the Eastern Boundary Current System

Cochairs: M. Ohman and B. Hickey

Participants: V. Holliday, A. Huyer, P. Kremer, A. MacCall, D. Mackas, K. Parker, W. Pearcy, J. Schumacher, T. Strub, R. Tipper, and D. Ware

**INTRODUCTION**

The California Current system (CCS) comprises three broadly definable regions: I, Vancouver Island to Cape Blanco; II, Cape Blanco to Point Conception; and III, Point Conception to northern Baja California (Fig. 5). These regions are characterized by differences in wind stress, intensity of coastal upwelling, coastal morphology, freshwater inflow, and influence of long-time-scale advection. The regions also differ in seasonality of planktonic production cycles. For some planktonic species, the regional boundaries represent biogeographic boundaries, although other species range throughout the three regions.

Among the most striking biological contrasts is the paucity of surface spawning by epipelagic fishes in the central region (II; see Parrish et al. 1981). This region is characterized by strong seasonal upwelling near coastal promontories and by a variety of mesoscale features such as coastal jets, eddies, and filaments that tend to transport organisms offshore. The fish species that do reproduce in this region tend to brood eggs or larvae, or to spawn demersally in protected waters. Equally striking is the concentration of spawning activity in Region III: about 90% of the epipelagic fish biomass (hake, sardine, anchovy) in the southern part of the California Current system spawns in the Southern California Bight and waters offshore. Primary and secondary production in Region III is therefore important to a significant fraction of California Current fishes.

A number of critical physical processes are likely to govern much of the variability in marine populations over time in the CCS and other eastern boundary currents:

- Mesoscale eddies, jets, and meanders
- Timing, duration, and intensity of coastal upwelling
- Vertical mixing events
- Alongshore advection

These processes may be influenced by future changes in the global ocean; some evidence suggests that changes have already occurred in recent decades. The differences in physical-biological linkages in Regions I, II, and III provide a natural basis for comparative study of the changes in marine populations that may accompany different scenarios for climate change.

We strongly recommend conducting comparative studies in all three regions of the CCS. Forcing functions differ spatially, but some marine species depend on processes in all three regions, so a successful GLOBEC program will have to incorporate the significant processes operating on a broad latitudinal scale. One component of this program should include intensive field studies that focus on processes thought to be important in each region. As a second component, we recommend time series sampling in each of the three regions for at least a decade. The time series might include a combination of moored arrays, satellite observations, and ship surveys. Suitable localities within each region might include the west coast of Vancouver Island, or the coasts of Washington or northern Oregon (Region I); Point Arena to Point Sur (Region II); and the Southern California Bight (Region III). In each region there are oceanographic institutions and shipboard resources that could be applied to the task. It is likely that existing field programs in each of the three regions could be expanded.

## REGIONS OF THE CALIFORNIA CURRENT SYSTEM

The California Current system spans more than 20 degrees of latitude along the west coast of North America. Its range exceeds the scales of dominant atmospheric pressure systems as well as the scales of regional coastal morphology. Thus the variability of the California Current and associated planktonic populations inherently includes significant and sometimes dramatic latitudinal differences. Many of these differences (e.g., wind forcing, temperature, photoperiod) are roughly a linear function of latitude, whereas others have distinct biogeographical boundaries. Examination of the dominant characteristics suggests that the California Current has three principal regions (Fig. 5). The boundaries between these regions are not exact, particularly between Regions I and II, where the area of seasonally reversing monthly mean winds extends farther south (to about 39°N) than the area of relatively straight coastline (about 420N). The boundaries are known to change during El Niño/Southern Oscillation and other long-term events, including intrusions of subarctic water from the north. The boundaries might also be expected to shift under some scenarios of global change.

In Region I, coastal wind stress is relatively strong, and wind direction reverses seasonally as well as on shorter time scales. Winter storms are particularly strong and frequent, leading to intense mixing and alongshore northward advection (Huyer et al. 1978; Thomson 1981; Hickey 1989; Thomson et al. 1989). Except for the region near the Strait of Juan de Fuca, the coastline is relatively straight, and the shelf is continuous, though narrow, over large alongshore scales (hundreds of km). Significant freshwater input is provided throughout most of the year by the Strait of Juan de Fuca and by the Columbia River. Large estuaries are relatively common and are thought to provide nurseries for several important species (e.g., Dungeness crab, McConnaughey et al., in press; Pacific herring, Haegele and Schweigert 1985). Primary production rates (Perry et al. 1989) and zooplankton biomass (Mackas 1992) have strong seasonal variations in this region. Some of the major copepod species overwinter at depth, then reappear in the surface layer for relatively short periods of growth in spring and summer. Several species (e.g., *Neocalanus plumchrus*, *N. cristatus*, *Eucalanus bungii*, *Calanus pacificus oceanicus*) enter Region I from the Subarctic Pacific or the West Wind Drift (Fleminger 1964; Fleminger and Hulseman 1973) and rarely extend south of this region.

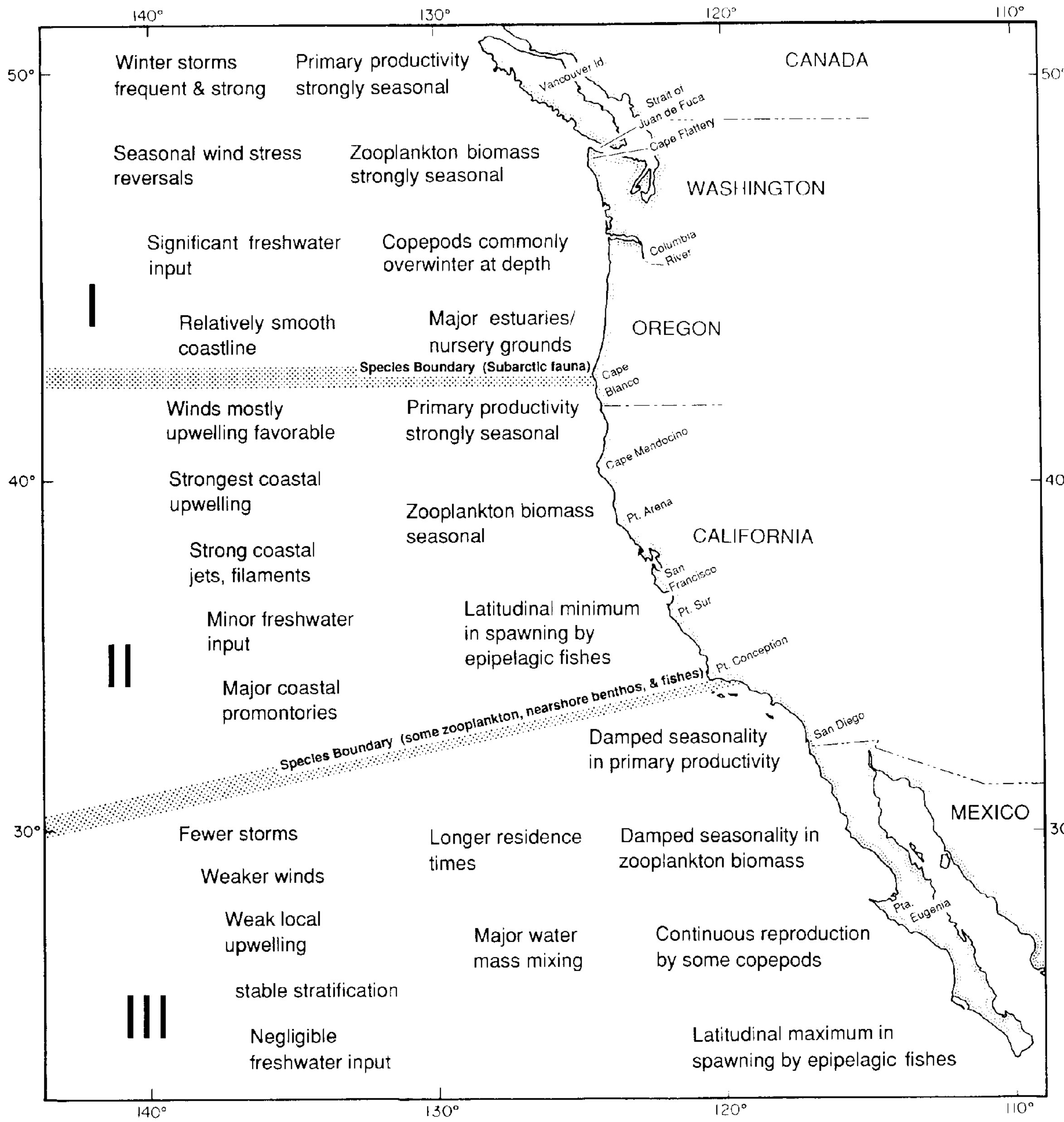


Figure 5. Generalized regional variations in physical and biological processes within the California Current System. The boundaries between Regions I, II, and III are only approximate and vary over time. The generalizations regarding Region III apply primarily to the Southern California Bight.

The dominant physical characteristics of Region II, which extends approximately from Cape Blanco to Point Conception, are the coastal promontories. Recent research suggests that energetic coastal jets, filaments, and meanders are associated with these promontories (Davis 1985; Kosro & Huyer 1986; Huyer & Kosro 1987; Strub et al. 1991). Current jets commonly extend 200-300 km offshore and may lead to relatively short residence times for plankton in the coastal zone. The strongest equatorward wind stress and, hence, coastal upwelling also occur in Region II (Nelson 1977; Huyer 1983; Strub et al. 1987). Although wind stress varies seasonally, the seasonal mean is always directed toward the equator. The strong coastal upwelling in this region supplies "new" nutrients into the euphotic zone, leading to elevated primary production rates and high standing stocks of phytoplankton (Dugdale & Wilkerson 1989). Satellite imagery suggests that many of the high-chlorophyll features found in Region II are associated with jets, eddies, and other mesoscale features (Flament et al. 1985). Zooplankton biomass varies seasonally (Roesler & Chelton 1987). Zooplankton species composition can shift relatively abruptly at the frontal boundaries associated with mesoscale jets and eddies. Among the most dramatic biological characteristics of Region II is the latitudinal minimum in spawning of pelagic fishes. Whereas epipelagic fishes spawn extensively in Region III and to some extent in Region I, those in Region II appear mainly to brood their eggs or larvae (e.g., rockfishes) or to use nearshore embayments as spawning and nursery grounds (e.g., Pacific herring) that appear to reduce the probability of offshore transport of pelagic larvae (Parrish et al. 1981).

The dominant physical characteristic of Region III is that, because of the coastline bend at Point Conception, local wind stress is relatively weak on the scales of seasons and events (Nelson 1977; Halliwell and Allen 1987). Thus local upwelling is weak in spring and summer, and wind- and wave-induced mixing is relatively weak year-round. Winter storms occur only occasionally. Freshwater input is insignificant. Interleaving of differing water masses occurs in Region III, making it particularly sensitive to large-scale, long-time-scale environmental perturbations such as ENSO (Hickey 1979; Lynn & Simpson 1987,1990; Tsuchiya 1980). Seasonal cycles in zooplankton biomass are relatively weak (Roesler & Chelton 1987). Deep overwintering of calanoid copepods occurs (Alldredge et al. 1984), but it may involve only part of a population while another part grows and reproduces year-round (Mullin & Brooks 1967). The boundary between Region II and III is a biogeographic boundary for some species of nearshore benthic marine invertebrates and pelagic fishes. Region III is the preferred spawning site for over 90% of the epipelagic fish biomass (hake, sardine, anchovy) in the southern part of the CCS.

In addition to these latitudinal patterns, strong cross-shore variations occur in the CCS. For example, the wind field has strong cross-shore gradients at most latitudes, with maximum winds occurring seaward of the continental shelf (Nelson 1977). Vertically integrated primary production rates tend to decrease in the cross-shore direction (P.E. Smith, pers. comm.; F. Chavez pers. comm; Perry et al. 1989). A zone of maximum variability in dynamic height begins approximately 200-300 km offshore (Lynn & Simpson 1987); this zone has been called an eddy alley. The long-term maximum in macrozooplankton biomass occurs offshore in some areas (Roesler & Chelton 1987). This maximum is sometimes dominated by gelatinous zooplankton such as salps and doliolids (Berner 1967).

## CRITICAL EASTERN BOUNDARY CURRENT PROCESSES AND BIOLOGICAL LINKAGES

We identify key physical-biological linkages that should be addressed in the GLOBEC eastern boundary current program. Each linkage focuses on physical processes thought to significantly affect population growth rates of metazoans having a planktonic stage. The relative importance of these processes typically differs in the three regions of the CCS. The regional differences may be viewed as a "natural experiment," permitting the relative impact of different processes to be quantified and perhaps used as a basis for projecting responses of marine populations to different scenarios of global change. We also pose a few preliminary hypotheses; we expect these to be modified and others to be put forward in future discussions.

### Mesoscale Eddies, Jets, and Meanders

Rationale: Physical features such as eddies, jets, and meanders of coastal currents can be highly energetic and variable over time. Planktonic organisms entrained within these features often experience increased offshore (or onshore) transport, as well as different regimes of food and predators. Behavioral adaptations to such features (e.g., diel vertical migration interacting with current shear) can increase the residence time of organisms in the coastal zone.

> $H_1$: Nearshore eddies, jets, and current meanders are significant dispersal mechanisms for coastal populations.
>
> $H_2$: Frontal zones associated with these mesoscale features are sites of enhanced production and concentration of planktonic prey.
>
> $H_3$: Offshore mesoscale eddies are retention sites that reduce spatial losses and enhance population growth rates of some planktonic populations.

### Timing, Duration, and Intensity of Coastal Upwelling

Rationale: Coastal upwelling influences planktonic organisms through a number of mechanisms. These include: (1) food-web effects (mediated by the input of "new" nutrients and elevated primary production); (2) seeding of epipelagic populations from dormant stages in deeper water; and (3) offshore transport of organisms entrained in upwelling filaments and jets. We emphasize the first two mechanisms here.

> $H_1$: Seeding from dormant stages is more important to population growth in Region II, where offshore transport is more frequent, than in Region I, where transport is more frequently alongshore.
>
> $H_2$: A significant fraction of the primary and secondary production in Region II is advected off the shelf and is unavailable to pelagic fishes that normally inhabit the continental shelf and slope (e.g., Pacific hake and northern anchovy).

**Vertical Mixing Events**

Rationale: (1) The shape and depth of the pycnocline affects the supply of new nutrients into the euphotic zone. This alters the magnitude of primary production as well as food-web structure (i.e., the size and species composition of phytoplankton and microzooplankton). Vertical mixing can change the pycnocline topography and thus food-web structure. (2) Lasker's "stable ocean hypothesis" suggests that "turbulent" mixing can erode the microscale aggregations of microplankton that are essential for the first-feeding success of some larval fishes. The intensity and frequency of storms can alter the availability of prey to a variety of different zooplankters. (3) Turbulence can affect the encounter rates of prey and predators. Recent studies suggest that encounter rates increase with turbulent kinetic energy dissipation (Yamazaki et al. 1991).

> $H_1$: There is an optimal wind speed that maximizes primary and hence secondary production. The optimal speed is about 7-8 m $s^{-1}$.
>
> $H_2$: Survival is greatest for fish larvae that hatch during calm conditions.

**Alongshore Advection: Long Time Scales**

Rationale: Biogeographic boundaries exist within the CCS, e.g., at Point Conception (the boundary of Regions II and III) and sometimes at the boundary between Regions I and II (Brinton 1962). With alterations in the large-scale circulation of the CCS, these biogeographic boundaries may shift, thereby affecting the survival patterns and spawning success of indigenous populations. Circulation changes may also introduce faunal elements from different biogeographic provinces (e.g., the subarctic Pacific or tropical waters; Pearcy and Schoener 1987). Benthic populations dependent upon particular substrates or sediment characteristics may change abruptly and nonlinearly if the required substrates are discontinuous along the coast and animals are displaced considerable distances alongshore.

> $H_1$: Large-scale advection from the north alters the species composition and secondary production of CCS zooplankton assemblages.
>
> $H_2$: Large-scale advection from the south during El Niño/Southern Oscillation alters the species composition and secondary production of CCS zooplankton assemblages.

**Alongshore Advection: Shorter Time Scales**

Rationale: "Spatial losses" of organisms from a desirable habitat or spawning grounds can result in marked depression of recruitment success (e.g., Bailey et al. 1982). Conversely, alongshore advection can also serve as an essential mechanism by allowing planktonic organisms to return upstream to favorable spawning grounds or habitats. Some aspects of alongshore advection are relatively predictable (e.g., seasonal reversal of winds and currents in Region I; the seasonal in Region I but not in Region III.

$H_1$: Some pelagic species need the poleward-flowing California Undercurrent and Davidson Current to complete their life history.

Each of these processes may fluctuate on a variety of time scales. For example, the frequency or intensity of upwelling-favorable winds may change within a single season, as well as over decades (Bakun 1990).

**RESEARCH STRATEGIES**

We recommend that two research strategies be pursued in parallel. The first is to study a long-lived, dominant species throughout its life history as it migrates through the different regions of the CCS. This might be characterized as a Lagrangian mode of study. The study site will shift with the ontogeny of the organism to investigate the processes leading to spawning success, larval and juvenile survival, latitudinal migrations, and adult feeding success. A particularly good candidate for this approach is the Pacific hake. Hake spawn in a geographically restricted area in the west of Region III, yet eventually migrate northward to Region I, where they are found as adults (Fig. 6). They may be seen as "integrators" of different processes in different regions of the CCS and therefore particularly sensitive to changes in ocean circulation and food-web structure. Preliminary evidence suggests that their spawning grounds moved northward in the late 1970s (inset, Fig. 6). The timing of this shift corresponds to a warming period in the ocean (A. MacCall, pers. comm.). Thus Pacific hake may be particularly sensitive to global change.

The second research strategy involves selecting species (or sibling species) that occur broadly throughout the CCS. It is hypothesized that the same species are governed by different processes in different regions. This strategy might be viewed as an Eulerian mode of study. In the different regions occupied by "metapopulations," or subpopulations, of the species, the differing effects of processes such as offshore transport, food limitation, vertical mixing, or large-scale advection can be quantified.

A simplified description of the population growth rate for a metapopulation within each of the three regions of the CCS can be expressed as follows:

$$dN_R / dt = \text{birth}_R - \text{death}_R - \text{horizontal migration}_R - \text{advection}_R + \text{diffusion}_R$$

where the subscript $_R$ designates the region of interest. The terms in the equation are each rather complex and nonlinear functions of other processes and will vary within (as well as between) regions. Nevertheless, in this Eulerian approach, strong regional contrasts in the importance of these terms should make it possible to identify the most significant population control mechanisms. For example, for cyprid larvae of barnacles, the advection term may predominate in Region II, and the death rate term may predominate in Region I.

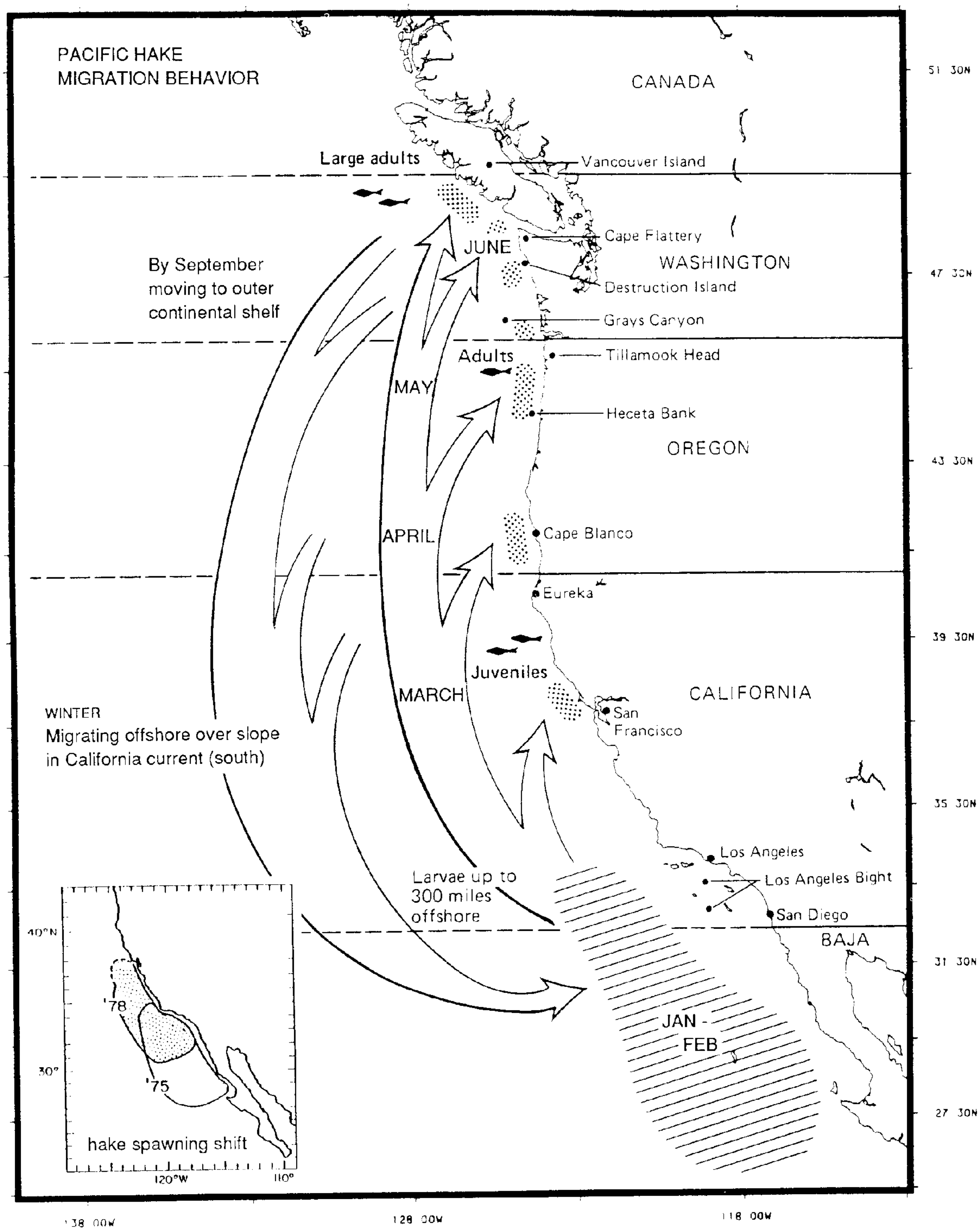


Figure 6. Migration of the Pacific hake, *Merluccius productus*, from Bailey et al. 1982; interpretation of timing modified by D. M. Ware. Inset illustrates the geographic shift in spawning area from 12975 to 1978 (P. E. Smith, pers. comm.). The northward displacement of spawing occurred at a time of warming in the California Current system (A. D. MacCall, pers. comm.).

## TARGET SPECIES

### Fish

Approximately 90% of the epipelagic fish biomass in the southern part of the California Current spawns in the southern California Bight and associated offshore waters (D. Ware, pers. comm.). The three primary species are Pacific hake, northern anchovy, and sardine (Ware and McFarlane 1989). Because hake constitute 50-60% of all epipelagic fish biomass, they are a particularly suitable target for this study, in addition to the reasons identified above. Recent evidence for recovery of the sardine (P. Smith, pers. comm.), combined with extensive historical information on the sardine and northern anchovy, suggests that they are also excellent candidates for study. Pacific hake and anchovy have spawning subpopulations in Region I as well as Region III and thus are good candidates for the Eulerian approach.

Although the spawning regions of the Pacific hake and northern anchovy overlap broadly, the two species show markedly different interannual variations in recruitment (Fig. 7). Hake have occasional very strong year classes, while northern anchovy tend to have runs of weaker or stronger year classes. This difference is a likely topic for GLOBEC studies.

### Holozooplankton

Target species of zooplankton include representative copepods, euphausiids, and a salp or doliolid. Some species are found in different regions of the CCS, exhibiting different life-history traits such as overwintering strategies and vertical migration in different parts of their ranges. Examples include the assemblage *Calanus pacificus oceanicus*, *C. pacificus californicus*, and *Calanus marshallae.* A copepod genus whose life history differs markedly from that of the genus *Calanus*, yet is also widely distributed in the CCS is the cyclopoid copepod *Oithona*. *Oithona* might be considered a "steady-state" genus in contrast to the "opportunistic" characteristics of *Calanus*. *Eucalanus bungii* and *E. californicus* are also likely to offer interesting contrasts.

With respect to euphausiids, *Euphausia pacifica* is distributed throughout the CCS, from the Gulf of Alaska to Baja California (Brinton 1962). It is the dominant species at many localities and makes an excellent candidate for contrasting studies in different regions of the CCS. The northern metapopulations of *E. pacifica* have shorter growing seasons and greater age and size at maturity than the southern metapopulations. Other potential candidates include *Thysanoessa spinifera* and congeners. Since euphausiids and copepods are the dominant prey for the target fish species identified above, we expect to advance understanding of the coupling between physical processes, zooplankton production, and fish recruitment.

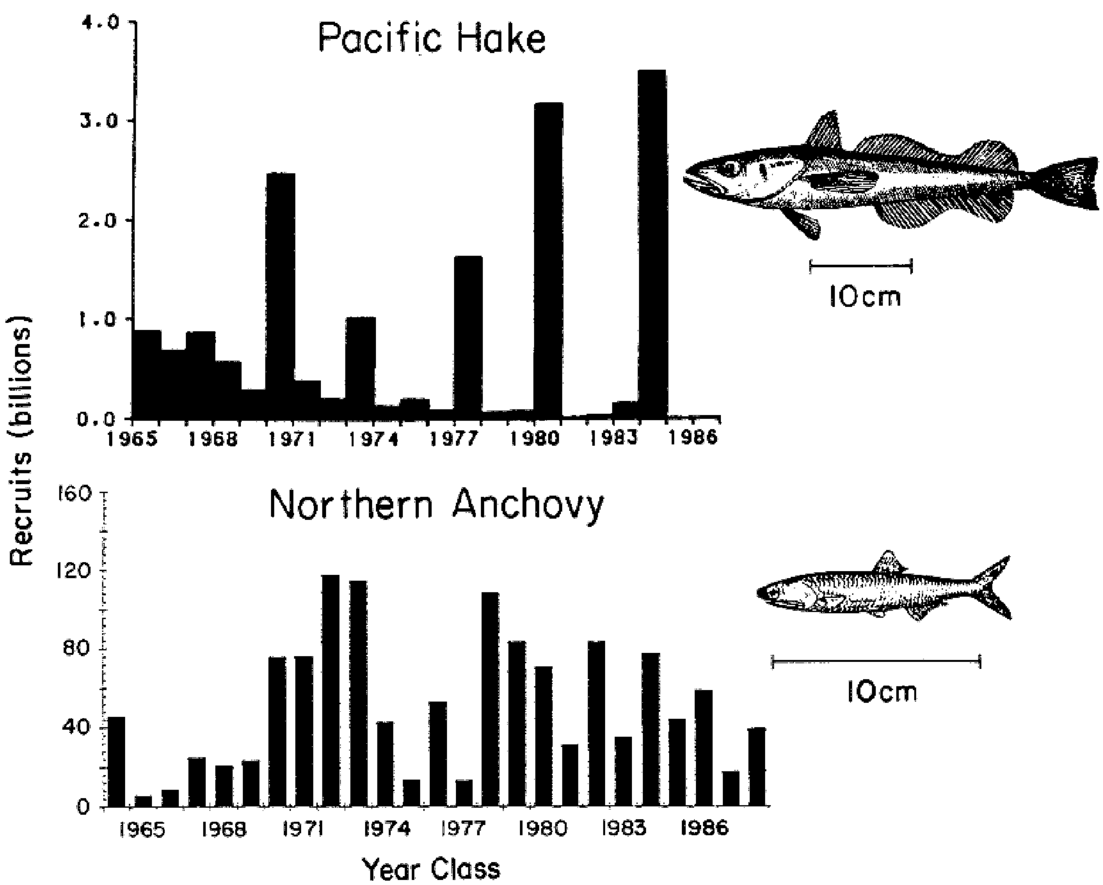


Figure 7. Comparative recruitment time series of Pacific hake (*Merluccius productus*; from Hollowed and Bailey 1989) and northern anchovy (*Engraulis mordax*; from Jacobson and Lo 1989).

Salps, and to a lesser extent doliolids, have extraordinarily rapid growth rates and colonizing abilities. Historical evidence suggests that they may predominate in some regions of the CCS (Berner 1967). It is also known that major ENSO events affect the total thaliacean (salp, doliolid, pyrosome) biomass much more than the copepod and euphausiid biomass (Smith 1985). Both observations suggest that a salp or doliolid species should also be a focus of study. Experiments should be designed expressly to understand the contrasting processes that select for either thaliacean or crustacean dominance, and the resulting consequences for the pelagic ecosystem.

**Benthos**

Among inhabitants of the hard-bottom benthos, the Dungeness crab and barnacles of the genera *Balanus* or *Cthamalus* have the best historical data bases and are likely candidates for further study. Evidence from some studies suggests that adult-adult interactions on the bottom may generally be more important for controlling community structure in Region I (e.g., Paine 1974), while cross-shore transport of pelagic larvae and migration of upwelling fronts may more significantly govern population growth in Region II (Roughgarden et al. 1988).

## 3.2 Importance of Mesoscale Physical Features to Ecological Processes in the California Current System

Cochairs: C.B. Miller and L. Washburn

Participants: K. Bailey, L. Botsford, A. Bucklin, R. Francis, W. Graham, P. Hsueh, J. Jaffe, B. Jones, D. Mackas, J. Paduan, T. Powell, L. Rosenfeld, and E. Woehler

Oceanographers have known for decades that the physical and biological characteristics of eastern boundary current ecosystems vary intensely in space, but until recently have lacked the observational tools for resolving the pattern of this variance. The discovery of filaments, squirts, and persistent eddies through satellite observation of eastern boundary current systems is one of the greatest viewpoint shifts since modern oceanography began after World War II. It ranks with the discovery of continuous midocean ridges and with finding submarine thermal vents and their associated communities. The existence of a massive, churning vortex system with (it now appears) close spatial association of physical and biological pattern was unexpected from all previous observation or theory. Exploration of interactions within this system has theoretical, practical, and public appeal. In every respect the recurring mesoscale-to-subregional flow features deserve extended examination. Within the California Current system, these features are most prominent off the central and northern California coast, and we recommend that their study be concentrated there. However, results from this region promise valuable insight for ecology in other eastern boundary current systems with comparable flow features.

## HYPOTHESES: THE ECOLOGICAL SIGNIFICANCE OF MESOSCALE FEATURES

The mere existence of central California filament features does not establish their importance to pelagic populations. We therefore pose the following null hypothesis:

> $H_0$: Squirts, jets, and filaments have no significance to the life of planktonic or other organisms.

This null hypothesis cannot be disproved by inspection from space. Rather, a program of direct testing is required. The test of the basic null hypothesis could be rather simple pair-wise sampling of populations within and outside of features. A more sophisticated test would require time series sampling following drift tracers, preferably without tethered surface floats. Sampling in the tracers' vicinity would allow comparison of the level and rate of change of demographic parameters (developmental progress, fecundity, condition factors, enzymatic capacity) for water parcels affected by and external to major mesoscale flow features.

Regardless of final complexity, the test(s) of the null hypothesis should be designed to provide maximum information about each of a number of alternative (and nearly *a priori*) hypotheses regarding ways in which the features are likely to have significant impact. We recommend that this list of alternative hypotheses include the following.

> $H_1$: Eddy features are retention/aggregation sites for meroplanktonic and holoplanktonic populations, and the demographic parameters of individuals inside and outside eddies will differ.

This can be examined by repeated sampling in an eddy feature identified by satellite imagery and marked with drifters interrogated in real time during sampling. The effort should last weeks to a month—long enough for significant progression of developmental stages in contained populations. Both cyclonic and anticyclonic eddies should be investigated to determine whether either has a greater tendency to retain material and persist longer, and whether biological interactions differ in the two types of eddy. In addition to demographic information, we recommend collecting information on within-species genetic resemblance of organisms inside and outside the eddies.

> $H_2$: Inshore stocks suffer major losses from seaward advection in streamers and filaments.

We are interested both in the magnitude of loss, and in the sensitivity of this loss to changing climatic conditions. There is already evidence that many populations have compensating behaviors that minimize such losses. Most benthic invertebrates with pelagic phases are winter spawners. Their larvae are at risk only during the season of minimal offshore transport. But there is increasing evidence that alongshore and temporal variation in settlement is linked to variation in nearshore upwelling circulation (Roughgarden et al. 1988; Ebert and Russell 1988). There are coastal holoplankton off southern California, where jet/eddy activity appears to be reduced compared with central California. It is not known to what extent the holoplankton are transported offshore during the season of most active upwelling. The data gathered to date (CTZ project) indicate that very few coastal holoplankton move seaward in the offshore flow fields associated with large filaments (Mackas et al. l991). Although good information is available from the Oregon coast (Peterson et al. 1979), cross-shore exchange of biota within the immediate coastal zone (0-20 km from shore) has not been studied off central California. Much more extensive sampling is also needed to establish the large-scale correspondence, if any, between the alongshore zone of extended upwelling features and distributional boundaries of populations.

> H3: Marine organisms actively exploit intense local gradients at the boundaries of mesoscale features.

Jets, filaments, and eddies exhibit strong, convergent secondary flows which produce sharp, persistent fronts. They may also carry localized pulses of dissolved nutrients and particulate food from onshore bands of high concentration into oligotrophic offshore waters. Thus squirts, filaments, and eddies that form off central California can accelerate food chain transfers in several ways: species may aggregate at sharp boundaries; predators may migrate there to eat them; and oceanic plankton mixed into extensions of onshore conditions may find luxuriant food and respond strongly through enhanced reproduction, higher growth rates, and improved condition factors (Mackas et al. 1991; Smith and Lane 1991). Some data suggest that this may particularly involve thaliacians (salps and doliolids), which have extremely rapid population growth responses. All of these trophic enhancement effects are amenable to study by classical and modern techniques of planktology (e.g., acoustical biomass estimation, enzymatic condition indices).

> H4: For at least some species, squirts, filaments, and their associated surface and deep return flows provide beneficial transfers at key life stages.

These transports might be either onshore or offshore. On this topic, sampling should be based on detailed hypotheses about the life history and requirements of particular species. Both the timing and the spatial distribution of sampling will have to match the developmental and transport schedules of species of interest.

## TIME-SCALE INTERACTIONS IN THE CALIFORNIA CURRENT SYSTEM

Physical and biological processes in the CCS have multiple time scales. Physical processes have at least interannual, annual, mesoscale event, weather, diel, inertial, and turbulent time scales. Pelagic organisms respond to habitat variations on all of these scales. They do so by different, scale-appropriate shifts in location and activity. Table 1 shows some of the correspondences among these time scales, physical process variations, and biological responses. Each physical process varies over a range of frequencies in the vicinity of those named. Likewise, some biological responses can adapt to physical processes on several time (and space) scales. Understanding this time-scale matching is a goal of all ecology; for GLOBEC, time-scale matching is an essential design consideration for CCS studies.

## APPROACHES TO MESOSCALE ECOLOGICAL PROCESSES VIA BIOMASS ESTIMATION

Biomass distributions, which may be characterized much more rapidly than species or stage distributions, can be used to test the importance and significance of mesoscale features. In particular, spatial surveys of acoustic biomass should rapidly settle the most basic questions of the ecological importance of mesoscale features. If mesoscale features transport large amounts of biomass, they are important to processes both upstream and downstream. The transport will be important to all the species making up that biomass, whatever they may happen to be.

The objectives of a survey of mesoscale variability will be ( 1) to determine the covariance of zooplankton distribution and flow features, (2) to determine the covariance of biomass size distribution and flow features, and (3) to measure the flow.

Coincident physical and biomass observations are required to meet these objectives. Deployment of acoustic biomass evaluation must be guided by recent satellite images of flow features. Sampling should be persistent enough to demonstrate the biota's delayed responses to flow features. This may well be possible if, for example, thaliacian population bursts are a major system response to translations of nearshore phytoplankton stocks and nutrients into the offshore zone. Spatial sampling should be fine enough to prevent aliasing; more than a few paired observations inside and outside features will be required. This requirement should not be overly stringent, given the data rates of emerging acoustical systems. The sampling distribution must also be more extensive than the flow features for adequate comparisons to emerge. The large size of these features creates a fairly heavy work load for the project. Sampling should resolve diurnal variation in biomass, since in the oceanic reaches into which filaments extend, major fractions of zooplankton biomass migrate vertically. In the CCS this includes some of the species most likely to be of interest to general GLOBEC goals (e.g., *Euphausia pacifica* and *Metridia pacifica*).

Equipment required for high-resolution biomass studies is under development, some of it with GLOBEC support. It should be noted that there are fundamental limitations to acoustic techniques. It will not be possible, because of physical limitations, to simultaneously and synoptically survey a large number of separate size classes in three dimensions. But we can develop systems at appropriate frequencies to map two-dimensional distributions of biomass with some size-class resolution. Physical data can be gathered at comparable density along these sections. Devices like the Pieper-Holliday towed, multi-frequency sonar will be appropriate. Suitably oriented sections will allow powerful tests of our hypotheses.

Table 1. Time-Scale Relationships Among Physical and Biological Processes in the CCS, Emphasizing Mesoscale Processes

| Frequency | Physical Events | Biological Responses |
|---|---|---|
| Annual | Alongshore jet formation/dissipation; high-low cycle in mesoscale activity. | Phenological responses (ontogenetic migrations, diapause, spawning migrations, selection of spawning timing, large scale horizontal migrations). |
| Semi-seasonal | Filament formation, extension, decay; eddy persistence. | Production and stock responses in zooplankton and small nekton (through spawning and growth variations); food storage, use of stored nutriment. |
| Weeks | Rotation period within features; feature translation alongshore. | "Vulnerability scale" - changes in life-stage maturation, reproductive activity. (Vulnerability to predators varies sharply with size, stage, and related escape capability. It may either decrease or increase with developmental progress). |
| Days | Weather, upwelling-downwelling cycle. | Production and stock responses in phytoplankton and microzooplankton; some mesoscale migratory responses? |
| Diel | Illumination cycle; local heating and cooling; convective turbulence cycling. | Daily vertical migrations; daily activity cycles including feeding, metabolism, mating, molting, etc. |
| Short Scales | Surface waves; internal waves; light flicker (hours to msec); cloud shifts; turbulent rotations in all axes. | Feeding bout cycling; swimming search patterns; near-field collision and predator avoidance; body orientation. |

## SPECIES OF INTEREST

Not all of the pelagic biota of the CCS can be addressed by GLOBEC. A modest number of species must be selected for intense biological study. The selection criteria should include the likelihood that an organism will significantly interact with mesoscale features. The working group accepted the GLOBEC focus on mesoplankton and larger pelagic animals, and developed a list of candidate species. These were evaluated under a list of suitability criteria, which were:

- Distribution - Does the species live in the central California Current and have potential for interaction with mesoscale features?

- Larval Period - Does this match or complement mesoscale activity?

- Data Base - Is information about spatial and temporal pattern for the species already available?

- Culture Potential - Rearable species are more readily studied.

- Biotechnological Potential - Biotechnical methods promise great insight, and species adaptable to such methods should be chosen.

- Paleontological Record - We can extend our understanding to time scales of global change by selecting species with fossil records, particularly high-resolution recent records.

- Commercial Value - Commercial value secures the sampling power of fisheries and assures the interest of the public and mission-oriented government agencies.

- Known Ecological Interactions - Certainty of interaction with other species of interest will be an advantage.

In accordance with the above criteria, workshop participants suggested the following list of species:

Fish: Northern anchovy, Pacific hake, California sardine, the rockfish complex, Dover sole, English sole, chinook salmon.

Benthos: *Cancer magister* (and various congeners as comparative cases); pink shrimp; *Emerita analoga*; barnacles (presumably *Balanus* spp. will be favored); sea urchins (*Strongylocentrotus franciscanus*, *S. purpuratus*); kelp.

Holoplankton:

Copepods: *Calanus pacificus*, *Metridia pacifica*, *Paracalanus parvus*

Euphausiids: *Euphausia pacifica*, *Nyctiphanes simplex*, *Thysanoessa spinifera*

Thaliacians: *Salpa* spp., *Thalia democratica*, *Dolioletta* spp. (study of gelatinous herbivores will have to be as opportunistic as they are.)

### 3.3 Paleo-oceanographic and Long-Term Historic Evidence of Past Variability

Cochairs: T. Baumgartner and L. Sautter

Participants: D. Ainley, M. Eakin, D. Hedgecock, A. Hollowed, M. Mullin, G. Rau, J. Rice, P. Smith, and L. Welling

Two major challenges that face GLOBEC are detecting ecosystem response to global change, and disentangling the effects of anthropogenic forcing from those induced by natural variability in the climate system. Knowledge of the past is vital to the design and implementation of programs to meet these challenges. Two exceptional and complementary sets of historical information - the high-resolution paleosedimentary record and the CalCOFI data set - offer a compelling argument for a California Current/eastern boundary GLOBEC initiative.

Several sites in the California Current contain anaerobic "sediment memories" of ecological variability over unusually short time scales of decadal, yearly, and even seasonal periods. Two confirmed sites and one potential site exist in the California Current system, plus an additional site in the Gulf of California, Mexico (Fig. 8). Information from these anaerobic sites has been used, for example, to reconstruct the biomass of northern anchovy and sardine populations over the last 2000 years, based on the abundance of their scales in the sediments of the Santa Barbara Basin (Fig. 9; Soutar and Isaacs 1974; Baumgartner et al. 1992). A variety of ecologic and geochemical information can also be extracted from sedimentary plankton remains to characterize the history of variability in the physical and biological environment in which the fish were living.

The CalCOFI data set documents the California Current ecosystem over the last four decades and offers a unique and ongoing opportunity to quantify the dynamics of populations and communities over interannual and decadal time scales. Integration of the paleoecological series and the historical CalCOFI data will be a powerful tool in the development of GLOBEC modeling and field sampling programs. Use of the CalCOFI information to interpret the high-resolution paleo-oceanographic record also helps us not just to describe, but also to understand the history of the California Current over the past century and back through at least two millennia. Conversely, modeling of ecosystem responses, based on present-day data, can be validated against the changes documented from the CalCOFI and the paleoecological data.

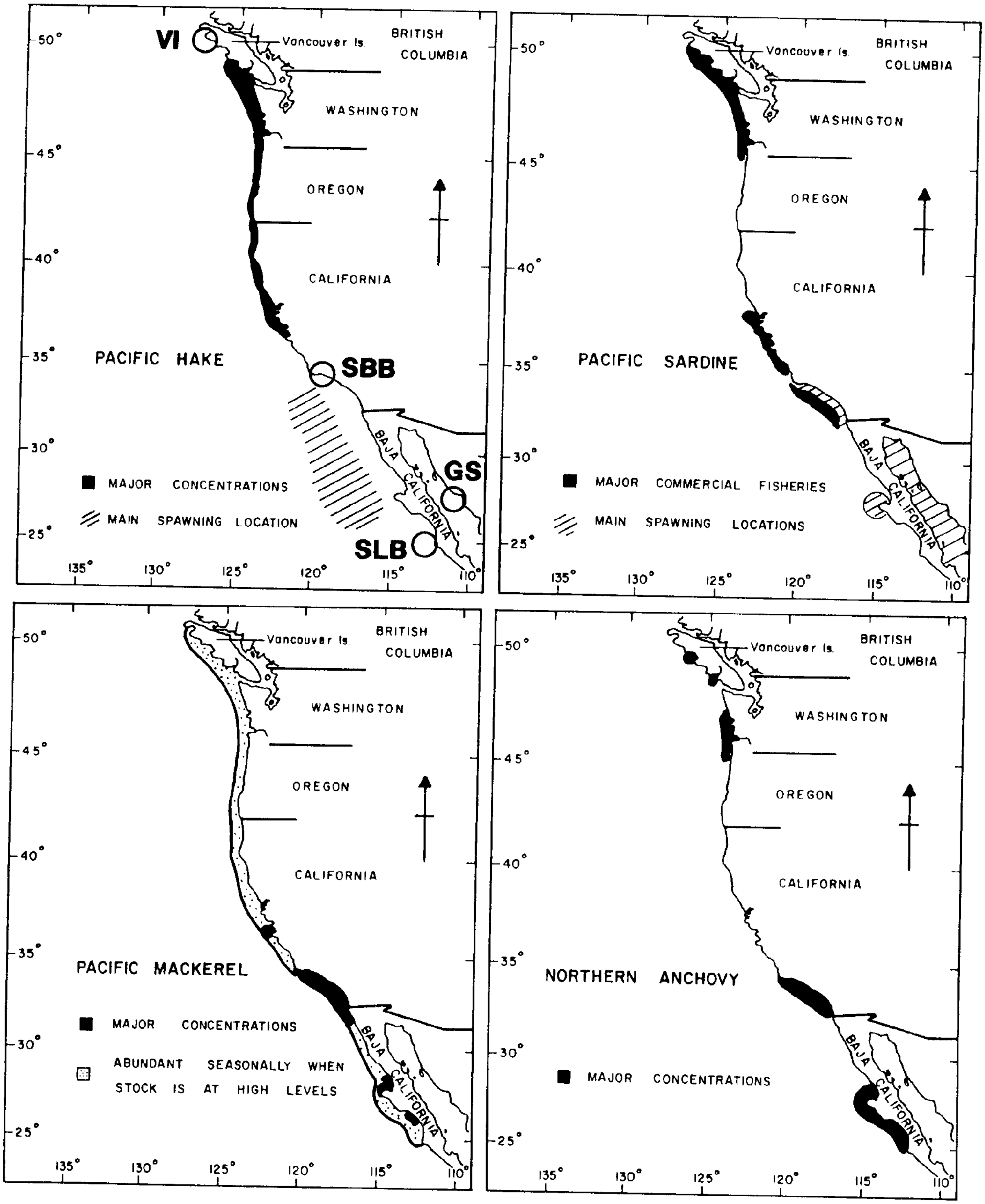


Figure 8. Circles in the upper left box indicate the known and potential sites for reconstructing the histories of coastal pelagic fish populations from anaerobic depositional environments. These are the fjords on the Pacific coast of Vancouver Island (VI; still untested for fish scales), the Santa Barbara Basin (SBB), the Soledad Basin (SLB), and the Guaymas Slope (GS) in the Gulf of California. The four charts indicate the principal areas of concentration and spawning of the four dominant coastal pelagic species during summer, according to the sources used by Ware and McFarlane (1989) for this compilation.

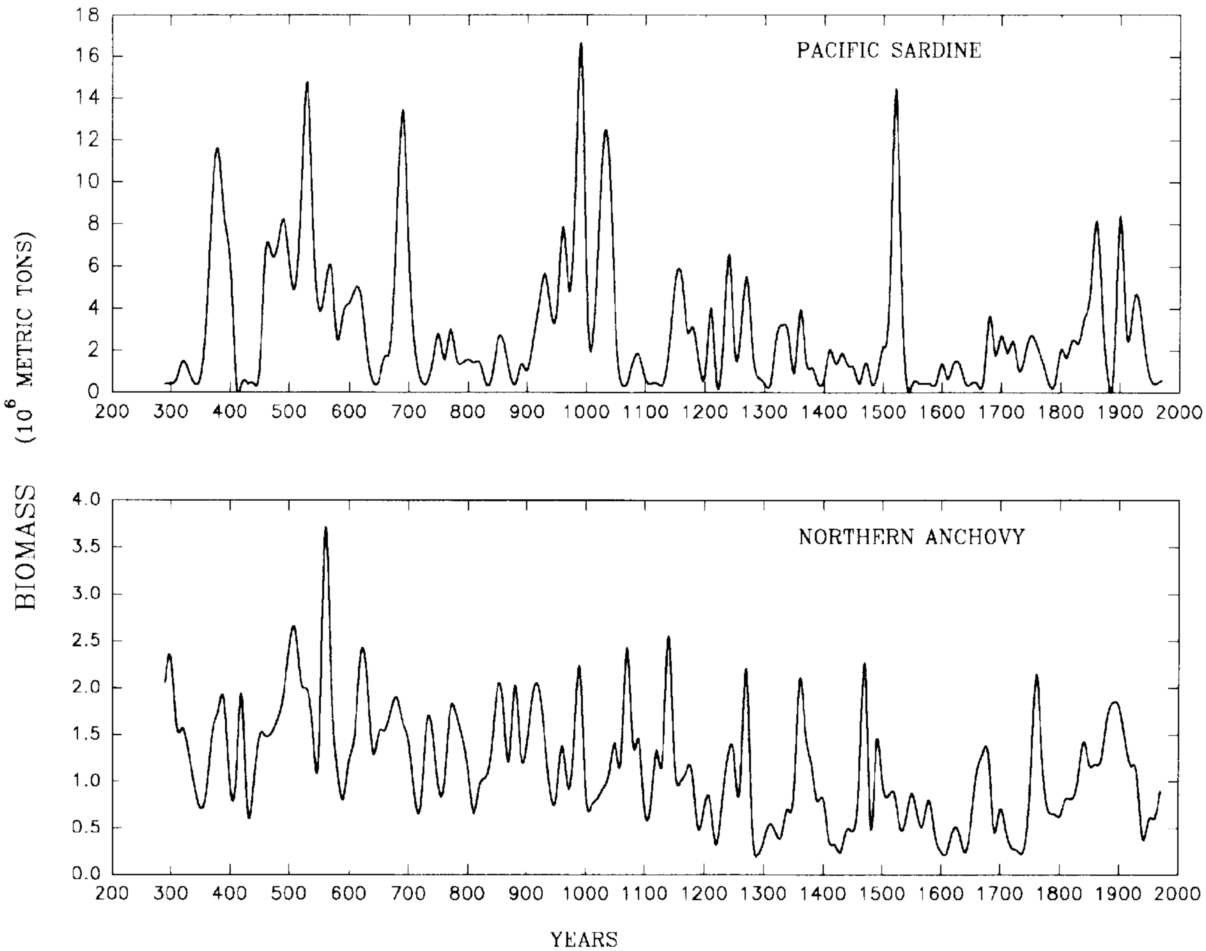


Figure 9. 1650-year proxy time series of biomass estimates for Pacific sardine and northern anchovy off California, based on the relationship between scale-deposition rates and modern population estimates (Baumgartner et al. 1992).

## KEY RESEARCH PROBLEMS AND APPROACHES

The working group began its session with informal presentations by several members. These emphasized the importance of key research questions or issues and led to a discussion on possible study sites, target species, and appropriate tools. By the end of the session, members had agreed that to understand how populations change on climatic time scales, we need to:

1. Determine the characteristic time scales and rates of change in the California Current ecosystem that are associated with global climate change. This requires extensive and detailed analysis of accurately dated, high-resolution sediment records.

2. Calibrate paleo-oceanographic records of population dynamics and environmental change against sediment-trap records to monitor present-day patterns in particle fluxes. This is necessary to determine the ways in which population change is transmitted to and preserved in the sediments. Sediment-trap studies offer a unique perspective on the ecology of fish and plankton species and lay the groundwork for reconstructing environmental settings. These studies will allow us to select appropriate plankton taxa as proxies for specific hydrographic conditions (e.g., Sautter and Thunell 1991) and will greatly amplify the value of fossil plankton (foraminifera, radiolaria, and diatoms) and fish remains as records of population shifts that reflect changing environmental conditions .

3. Use historical data bases and sample archives from CalCOFI to document changes in populations and communities and their relationships to global climate changes. The Scripps Institution of Oceanography, the Southwest Fisheries Science Center of NOAA/NMFS, and the California Department of Fish and Game have archives of fish and plankton samples as well as ancillary hydrographic and biological data from the late 1930s to the present, with continuous surveys of key areas since 1951.

4. Extrapolate the basin-specific paleoenvironmental records from the Southern California Bight to population and environmental changes over a wider geographic region of the CCS using contemporary sediment-trap studies. Sediment-trap data can test the generality of the Santa Barbara Basin fish-scale record with respect to the larger habitat of the fish and can relate scale-deposition rates to current biomass estimates of target species.

5. Explore promising sites for high-resolution paleo-oceanographic records outside the Southern California Bight along the west coast of North America (Fig. 8). The silled fjords in British Columbia have not yet been adequately searched for preserved fish scales. The existence of a fish-scale record in Soledad Basin off southern Baja California has been documented (Soutar and Isaacs 1974) but not well developed. Exploration and development of the information from these sites will yield a fuller description of spatial variability in conjunction with the long-term records.

6. Integrate sediment-trap-based flux studies into a long-term monitoring program to collect continuous seasonal, interannual, and decadal information about the ecosystem. This program would be part of the long-term GLOBEC monitoring study outlined in section 3.7 of this report. Such monitoring of selected sites and variables should be continued at least 20 years after the intensive studies of GLOBEC are concluded, to make sure that contemporaneous ecosystem change is detected.

7. Use paleo-oceanographic and historical data sets to constrain and test oceanographic and population models. Past changes in fish abundances from the sedimentary record can be used to constrain contemporary models of climatic effects on fish population dynamics. The quality of the information now emerging will be improved by finer sampling intervals in the long record. We envision a detailed study (e.g., two-year sample intervals) comparing contemporary twentieth-century warming with the medieval warming event that occurred between A.D. 900 and 1300.

## TOOLS AND METHODOLOGIES

### Documentation and Interpretation of the High-Resolution Sedimentary Record

The components available for study from the sediments are preserved hard parts of animals (e.g., fish scales, foram shells, and radiolarian skeletons) and phytoplankton (mostly diatom valves); bulk measurements of organic carbon and nitrogen, and of carbonate and silica; and the inorganic and organic elemental, isotopic, and molecular constituents of the fossil material (e.g. ,trace metals, stable light isotopes, lipid biomarkers, and genetic material). Ambient concentrations of some trace metals (barium, cadmium) and stable isotopes ($\partial^{18}O$ and $\partial^{13}C$) are preserved in the shells of planktonic foraminifera, providing information about changes in the upper water column's chemical and physical properties. Fish scales preserved in the anaerobic sediments allow us to study the variability of the pelagic species important to GLOBEC, such as hake, sardines, and anchovies.

### Analysis of Data Archives from Historical Collections

The 40 years of CalCOFI data and samples represent a rare opportunity to document variation in zooplankton populations and community structure and to link these with known changes in climate and ocean circulation. It is also possible to use plankton species archived by CalCOFI to investigate the variation in carbon and nitrogen dynamics in the CCS by measuring changes in stable isotope abundances, and to examine genetic variation by sequencing DNA in formalin-preserved specimens. Historic variations of $^{13}C/^{12}C$ and $^{15}N/^{14}N$ ratios within low-trophic-level zooplankton biomass will point to changes in carbon and nitrogen biogeochemistry within the CCS. Isotopic variation within these samples will help researchers interpret isotopic signals of the much-longer-term sedimentary record.

Finally, the relationship between scale-deposition rates from the Santa Barbara Basin sediments and the biomass of pelagic fish populations is still not well determined. There is only a brief overlap (eight data points using 5-year averages in Soutar and Isaacs

1974) between the existing sedimentary data and the fish population estimates (1932-69). We now have better population estimates and evidence of significant population changes for the period since 1970. Therefore, we can significantly improve calibration of scale-deposition rates by updating the sedimentary record and its relationship to the improved biomass estimates.

**Calibration of the Sedimentary Record Through Sediment Trap Studies**

Moored sediment traps are necessary in order to understand the transformation processes of material descending to the seafloor. Such traps also make it possible to the calibrate the sedimentary record to the overlying waters. Automated time-series traps and single-cup collectors should be used together. The spatial variability in deposition rates of pelagic fish scales should be assessed by multiple moorings of single-cup collectors. High-resolution time series of weekly, or at most biweekly, collections are needed to link particulate flux to hydrographic and biotic changes in the California Current. The sediment trap results will provide a continuous series of "snapshots" of the plankton between the quarterly CalCOFI cruises.

These studies would be enhanced if done in conjunction with the intensive field studies of the GLOBEC program. If the intensive field studies were augmented with sediment-trap information, we could observe how planktonic responses to ocean physics and associated biological productivity are preserved in the sedimentary record . We also could determine if fossil plankton taxa could be used as proxies for other plankton (especially fish larvae) not preserved in the sedimentary record.

## 3.4 Nutrient Input Mechanisms in Eastern Boundary Current Regimes

Cochairs: F. Chavez and L. Walstad

Participants: K. Bailey, P. Bernal, T. Hayward, A. Huyer, R. Iturriaga, D. Mackas, M. Mullin, I. Perry, B. Prezelin, L. Shapiro, R. Smith, and T. Strub

**OVERALL RECOMMENDATION**

Because new nutrients and primary producers may play a significant role in upper trophic level structure and abundance, we recommend the following hypotheses as appropriate for GLOBEC research within the California Current system:

> $H_1$: The overall carrying capacity of pelagic and benthic animal populations in eastern boundary current systems is a function of the input of new nutrients and the phytoplankton populations that result from them.
>
> $H_2$: The dominance of a particular animal population within a trophic level (taxonomic groupings or the ecosystem) are indirectly but causally coupled to changes in nutrient inputs. (An example of this is the long-time-scale alternation of dominance between the anchovy and sardine. Is this alternation related to variable new-nutrient input?)

H3: The temporal and spatial distribution of food quality (size, composition, physiological state) is tightly coupled to local rate of nutrient flux and, in turn, significantly affects community structure in the upper trophic level. A subsidiary hypothesis is that the form and magnitude of impact systematically varies with trophic level.

H4: Physical forcing of nutrient flux varies and is sensitive to global change processes, and this variability will be reflected in the population dynamics of the secondary producers.

## MECHANISMS OF NEW NUTRIENT INPUT IN EASTERN BOUNDARY CURRENT SYSTEMS

Eastern boundary regions are areas of enhanced primary production relative to the open ocean and western boundary current systems. Recent measurements (Jahnke et al. 1990) suggest that half the flux of organic carbon to the seafloor across the northeast Pacific occurs in the eastern boundary within 500 km of the continental slope. Clearly, eastern boundary current systems and their strong coastal circulation patterns are major oceanographic features that determine the physical, chemical, and biological character of a large portion of the global ocean. Biological production in eastern boundaries is enhanced because the thermocline, pycnocline, and - more important - the nutricline are in contact with the mixed layer and the euphotic zone (Barber and Chavez 1986). In eastern boundary upwelling regions such as the California Current system, the flux of new nutrients to the euphotic zone, primary production, downward particulate carbon flux, and fish production are all enhanced relative to the open ocean. Recent work by Walsh (1991) supports the view that continental margins, and in particular eastern boundary systems, are important in the global carbon and nitrogen biogeochemical cycles. Walsh has estimated that the supply of new nutrients to the euphotic zone (i.e., potential new production) along continental margins is equivalent to the flux of carbon to the deep sea in the open ocean.

Locally driven vertical transport processes and primary production are connected through the rate of nutrient supply to the surface sunlight layer. But local upwelling and mixing, although necessary, are not sufficient conditions for high rates of primary production. The second necessary condition lies in the nutrient content of the subsurface water that is advected, or mixed, into the surface layer. When the thermocline and the nutricline are depressed, the subsurface reservoir of nutrients is pushed deeper (Barber and Chavez 1986; Chavez et al. 1991). Current meter observations of coastal upwelling (Barber and Smith 1981) have shown that the water entrained by wind-driven upwelling comes from relatively shallow depths, on the order of 40 to 80 meters.

Processes that change the depth of the nutricline, as well as local upwelling or mixing, are therefore important in determining the biological richness of eastern boundaries. These processes can be separated into those that are remotely forced and large-scale, and those that are locally forced. Examples of large-scale forcing are the El Niño/Southern Oscillation cycle and, to some extent, the seasonal cycle. El Niño phenomena are discussed at length in a separate section. During strong ENSOs the nutrient supply decreases as the thermocline and nutricline deepen. This deepening results from Kelvin waves generated in the western equatorial Pacific that travel along the equator to the eastern boundary and then toward both poles (Enfield and Allen 1980; Pares-Sierra and O'Brien 1989) . The Kelvin waves are responsible for near-coastal anomalies, which propagate offshore as Rossby waves leading to the larger-scale eastern boundary anomalies (Pares-Sierra and O'Brien 1989). Changes in the local upwelling-favorable winds during El Niño are less predictable, apparently strengthening during some episodes and weakening during others.

Three oceanographic seasons have been described for central California (Bolin and Abbott 1963), but they do not necessarily hold for the entire California Current system. The seasons are not directly related to the local wind field (on the kilometer scale) but seem to be partly related to the larger-scale (northeast Pacific scale) seasonal cycle of winds. This larger-scale seasonal cycle has notable latitudinal gradients; one important difference is that south of about 37°N, upwelling-favorable winds exist year-round, whereas to the north there are more winter storms and consequently downwelling-favorable winds in winter. The spring transition occurs every year between February and April (Strub and James 1988). During this event, the high-pressure system in the northeast Pacific expands dramatically, causing favorable winds over a large part of the current system. The thermocline becomes shallower, and very cold and nutrient-rich water surfaces next to the coast. The upwelling period typically persists until July or August. At this time, the central California seasonal cycle in temperature structure uncouples from the seasonal cycle in upwelling-favorable winds; the deepening of the thermocline that occurs during July and August of every year is not accompanied by significant reductions in the upwelling-favorable winds. This "oceanic period" (Bolin and Abbott 1963) is one of increased stratification and occasional outbreaks of red-tide dinoflagellates in central California. Finally, the fall transition signals the beginning of the winter storm period; horizontal and vertical gradients diminish, and the Davidson Current flows over the shelf and slope in a predominantly northward direction all along the central California coast (Skosberg 1936; Hickey 1979; Chelton 1984).

Examples of mesoscale forcing that raise the levels of nutrients at the sea surface are coastal upwelling, the circulation patterns associated with mesoscale jets and eddies, and - to some extent - winter mixing. The nutricline shoaling associated with coastal upwelling, jets, and eddies results in a strong relationship between upper-ocean nutrient content and geopotential anomaly off central California. This suggests that the concentration of upper-ocean nutrients can be estimated from satellite-based sea-surface altimetry. The mesoscale relationship between sea-surface height and phytoplankton biomass is less clear than the relationship with nutrient concentration. However, in the central California region - where jets and eddies are most energetic - levels of phytoplankton biomass and rates of primary production are generally high (Abbott and Zion 1985; Hood et al. 1990; Chavez et al. 1991). The high rates of primary production in filaments may be related to local upwelling along the jet edge rather than advection of coastal upwelled water offshore. The strong baroclinic jets commonly found in central and northern California have been found to transport low salinity (Huyer et al. 1991) and low-nutrient water (Chavez et al. 1991) from the north on their offshore flanks.

In summary, a range of physical processes in eastern boundary current systems collectively causes relatively high levels of new nutrients at the sea surface. Less is known about the temporal and spatial distribution of regenerated nutrients. At present, we cannot predict the cumulative effect of climate variability at decadal time scales.

However, time series of nutrients from the eastern boundary system of the South Pacific (Chavez 1987) suggest that the total variance of nutrient concentration is dominated by the longest observed time scales, in much the way that temperature and sea level are affected (Steele 1985).

## 3.5 El Niño/Southern Oscillation (ENSO) Effects Within the California Current System

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El Niño represents an environmental extreme in the eastern boundary regions of the Pacific Ocean. Because of the extent of its effect on ecological structure and the economy, it has high visibility in the media and in politics. There have been 43 "strong to very strong" El Niño events in the five centuries since written accounts of climate and weather were first made in the Americas, with the most recent strong events being in 1982-83, 1972-73, 1957-58, and 1940-41 (Quinn et al. 1987). If one includes "moderate" El Niño events as well, the total rises to 117, although not all were manifested to midlatitudes. A strong El Niño every 10 to 20 years appears to be typical. Any research program in the California Current system extending for a decade or longer should therefore expect to encounter El Niño conditions, and - because El Niño represents an important mode of environmental variability in this region - a study of these conditions should be included in any GLOBEC plan for the California Current system.

The working group focused on three topics:

1. Expression of El Niño in large-scale and mesoscale physical and biological oceanography, and the availability of historical information

2. Potential variation under climate change

3. Contingency planning for additions and modifications to the overall field sampling program during El Niño years.

### OCEANOGRAPHIC EXPRESSION OF EL NIÑO: WHAT IT IS AND WHAT WE CAN EXPECT IN THE CALIFORNIA CURRENT SYSTEM

It is presently thought that El Niño events represent one phase of an irregular oscillation involving both the atmosphere and the ocean. Since the atmospheric component is called the Southern Oscillation, the complete, coupled phenomenon is referred to as the El Niño/ Southern Oscillation (ENSO). Physical scientists' understanding of ENSO events has improved (Kerr 1992), but probably not yet enough to predict El Niño with the confidence desired for committing major resources requiring long lead time, especially ships, to a major field effort. The present conceptual and numerical models do, however, provide excellent diagnostic and descriptive information.

The oceanic component of El Niño begins in the western Pacific and reaches the California Current region by two routes: oceanic and atmospheric. The oceanic signal propagates eastward along the equator from the western Pacific as an equatorially trapped baroclinic Kelvin wave, manifested as a deepening of the thermocline and a rise in SST and sea level. Upon reaching the eastern boundary of the Pacific, it propagates poleward in both hemispheres as a baroclinic coastal-trapped Kelvin wave at a speed of about 25 m/s. Thus, the rise in sea level and deepening of the thermocline along the midlatitude coast (30° to 50° latitude) occurs within months of the appearance of El Niño in the eastern equatorial Pacific. This initial effect is confined to within about 100 km of the coast. Increased poleward geostrophic flow is consistent with a deeper thermocline and higher sea level along the coast; early in the 1982-83 El Niño, the coastal currents off Oregon and Peru flowed strongly poleward (Huyer and Smith 1985).

As the coastal Kelvin wave propagates poleward along the eastern boundary, some El Niño signal also radiates westward from the eastern boundary as a Rossby wave with phase speed of only a few cm/s (Johnson and O'Brien 1990). Thus, at latitudes of the California Current, one might observe an anomalous deepening of the thermocline several hundred km offshore a year or two after warming of coastal waters has been observed. While the propagation of El Niño effects along the equator and coast as Kelvin waves has been clearly observed, the westward offshore propagation of El Niño in the form of Rossby waves in midlatitudes has only been shown in theory and suggested as an explanation for anomalous warm water in the offshore region a year or so after El Niño.

The large change in the sea-surface temperature of the equatorial Pacific during El Niño can also cause major changes in the position and strength of the atmospheric pressure patterns affecting the California Current region. During the El Niño winter of 1982-83, the atmospheric Aleutian Low strengthened and moved southward, causing severe storms along the California and Oregon coasts. The result was increased rainfall, increased vertical mixing, and increased onshore Ekman transport. During some El Niño events, however, the Aleutian Low strengthens but remains farther offshore, diverting storms to the north of their normal track (e.g., the California drought during El Niño 1976-77). The response of the coastal winds, which drive coastal upwelling, to El Niño is varied: although the coastal upwelling index was anomalously low off California in early 1983, the index was higher than normal off Peru. But despite the upwelling-favorable winds, nutrient inputs to the surface layer off Peru were low because the nutricline was anomalously deep and beyond the effects of coastal upwelling.

The biological effects of El Niño are less well documented than the physical effects. This is partly because descriptions of "normal" conditions are insufficient. But some generalizations can be made. The biological effects of El Niño stem in part from the deepening of the nutricline, and from the possible decrease in coastal upwelling. Although a deepening nutricline in the eastern Pacific should always be expected during El Niño, coastal upwelling does not necessarily weaken. As noted above, the net effect on nutrient input maybe equivalent, since the nutricline is deepened . Analysis of remote sensing data suggests that chlorophyll and, presumably, primary productivity decrease, although this has not been clearly established. A change in phytoplankton species composition has been documented in the Southern Hemisphere (Avaria and Munoz 1987). A large decrease in macrozooplankton biomass and in the abundance of some fish has been documented in both hemispheres (Chelton et al. 1982; Carrasco and Santander

1987). Large changes in patterns of distribution and abundance of some species of macrozooplankton and nekton have also been observed (e.g. ,Pearcy and Schoener 1987). Some of these changes in distribution are due to active migration; some are due to passive transport with the water; and others are likely due to in situ changes in population dynamics.

The California Current contains a rich pattern of low-frequency variability in biological and physical structure. The interannual variability in some physical and biological properties (e.g., in offshore steric height and in zooplankton abundance) is larger than the annual cycle. The question can be asked whether El Niño represents an extreme condition along a continuum of interannual environmental variability, or a qualitative change in environmental structure as well as an extreme in the range of environmental condition. There is insufficient information to answer this question, but the conceptual model that is chosen will affect the structure of models of biological response to El Niño.

The oceanographic community is probably aware of most data sources useful for describing the mid-latitude effects of El Niño (see, for example, the collection of papers on El Niño in J. Geophys. Res. 92(Cl3), 1987). The observations and monitoring necessary to answer many of the questions concerning effects of El Niño on the California Current region and its mesoscale features and variability have not been made. Coastal sea-level records, SST data, and biological monitoring over the decades indicate clearly that El Niño occurs along the coast, but repeated observations in the full California Current are much rarer. Some useful data are available from CalCOFI cruises, and from cruises by Oregon State University in the 1960s and 1970s, but the observations were on spatial scales too large to answer questions about the mesoscale.

**POTENTIAL VARIATION UNDER CLIMATE CHANGE**

The working hypothesis appropriate at this time is that in a globally warmed climate, El Niño events would occur with a frequency and intensity at least as great as in the present climate. Some recent preliminary studies (Zebiak and Cane l991) with a dynamic ENSO prediction model suggest that a warmer ocean, such as might result from global climate change, could increase the frequency and intensity of El Niño events.

The discussion was broadened to include the response of eastern boundary currents to global warming. It is difficult to predict any change in eastern boundary currents resulting from global warming on the basis of present general circulation models, which indicate a zonally uniform warming (1-2°C) of the oceans at 30° to 50°N. The oceanic components of the models have latitude/longitude resolution of several degrees, and therefore cannot adequately resolve eastern boundary currents. Thus the potential for increased warming in coastal regions due to a weakening in the eastern boundary current, which is caused by weaker atmospheric circulation caused in turn by reduced poleward temperature gradients, is not included in these models. Observations and physical reasoning indicate that increased warming of coastal land surface relative to the coastal ocean would increase coastal circulation and upwelling (Bakun 1990). Thus global warming might bring about two competing, and possibly offsetting, effects: a widespread warming but a local cooling in the coastal region of eastern boundary currents. If so, this would increase the zonal temperature gradient between the coastal and offshore regions and would enhance the likelihood of mesoscale variability in the coastal transition zone.

## SPECIAL REQUIREMENTS FOR SAMPLING DURING AN EL NIÑO EVENT

On the basis of present understanding it should be assumed that El Niño events will continue to occur with at least the same frequency and intensity as during recent centuries. Because El Niño represents an expected environmental extreme and because we need to know how eastern boundary current ecosystems respond to environmental extremes, it should ideally be an important GLOBEC goal to ensure that a full field program takes place in the California Current ecosystem during El Niño conditions. This is because the present ecosystem must contend with these conditions on an irregular basis, and much can be learned from comparing the extreme structure with more normal conditions. However, present prediction schemes (models) cannot confidently predict El Niño far enough in advance to schedule a full field program complete with major ships. Nevertheless, at the least, a limited study aimed toward understanding the effects of El Niño in the context of the major GLOBEC field programs should be developed. Such studies could be planned and launched several months in advance on the basis of early El Niño predictions.

Some level of monitoring will be necessary throughout the period of GLOBEC studies in the California Current region, independent of the phenomenon of El Niño. It is important to include in the monitoring some of the phenomena that may be affected by, or transmit the effects of, El Niño. Several studies will have been made in the California Current region before GLOBEC study begins. These should be useful for designing both the monitoring and the field program for studying El Niño.

Although we cannot make complete recommendations for an El Niño study within the context of a GLOBEC field program until the nature of that overall field program becomes more definite, it is clear that research on El Niño should be an important part of the overall design. We can at this time list elements of an El Niño study that are likely to contribute valuable information to understanding the California Current in the context of the GLOBEC program. Some of the key components would be:

- Moorings to monitor the poleward undercurrent over the continental margin. Poleward flow along the coast probably increases during El Niño and may be the major contribution to the advective changes observed. The strength of the undercurrent, and its interaction with topography, would affect mesoscale variability in the region, since the poleward flow affects the dynamical stability of the flow regime.

- Moorings offshore to monitor propagation of Rossby waves westward from the coastal region. In the models, Rossby waves are the mechanism that carry El Niño to the offshore ocean.

- Sediment traps on the moorings to document variability in the amount and composition of plankton and sedimenting particulate matter.

• Analysis of existing data, especially historical data on plankton distributions, to better understand "normal" conditions so that changes due to El Niño can be documented.

• Observations to assess the mesoscale structure and spatial distributions of the biota. The satellite altimetry data becoming available should help identify regions where mesoscale activity is particularly large in the near-surface current fields. Past and future satellite color scanner data should be similarly useful for some biological fields. Results from recent studies in the northern California Current region within a couple of hundred kilometers of the coast, and data from the larger domain accessible to satellite sensors, should make it possible to develop a monitoring and field program plan that would be sensitive to mesoscale variability and the effects of El Niño.

• Coupling of the physical and biological models. This could be done now by including biology in the present El Niño models. This would help clarify the putative effects of El Niño on the ecology and environment. At present, El Niño effects are best resolved in some of the physical and higher-trophic-level data; the linkage through the phytoplankton is less clear. The early initiation of coupled physical/biological modeling would also provide scientific publicity for GLOBEC.

**SUMMARY**

1. El Niño is an important environmental extreme in the ecosystem, and its conditions should be carefully sampled during an eastern boundary current GLOBEC program. This should not be solely a contingency plan to deal with an unexpected event, but rather an active plan to ensure that sufficient sampling will take place during El Niño conditions.

2. We should encourage the development of coupled physical/ biological models in eastern boundary current regions, especially with respect to mesoscale structure; El Niño conditions should be included in these models. This effort will be most valuable if significant results are available before field programs are planned.

3. Some monitoring will be necessary to place GLOBEC field programs within the context of low-frequency variability. El Niño is only one aspect of a rich pattern of low-frequency variability, and other processes of forcing and response deserve study.

4. The nature and extent of field work targeted specifically toward El Niño will depend upon the nature of the GLOBEC field program. El Niño studies should be an integral part of a field program, and should be included in planning from the earliest possible stage.

## 3.6 Special Tools

### 3.6.1 Technological Needs for Eastern Boundary Current Experiments

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A recent GLOBEC report on acoustical and optical technology (Holliday et al. 1991) detailed the needs common to all GLOBEC study sites. In this report we discuss the methodologies specific to an eastern boundary current program, including data processing, storage, retrieval, and sharing by the community, acoustic and optical techniques; and molecular biological techniques.

**ACOUSTICS**

Two approaches discussed by Holliday et al. (1991) and currently supported by GLOBEC are particularly important to eastern boundary current studies. D. Van Holliday is developing multifrequency acoustics to map size classes at a single location as a function of depth. His instrument, which can be used in either a moored or drifter mode, contains a string of eight dual-frequency sonars at 165 kHz and 1.1 MHz that will be deployed vertically in the water column. This distribution of frequencies allows the system to map the densities of centimeter-sized and millimeter-sized organisms. In addition, a dual beam system capable of judging target strengths will be deployed. Finally, an eight-frequency system will measure biomass and size distribution. The system uses real-time two-way telemetry.

Another system being developed under GLOBEC by J. Jaffe at the Scripps Institution of Oceanography's Marine Physical Laboratory (MPL) is a three-dimensional acoustic imaging system. Other systems are being developed at Woods Hole Oceanographic Institute (T. Stanton) and at the Applied Physics Lab at the University of Washington (E. Belcher). These systems can rapidly estimate biomass in a three-dimensional volume. The MPL system, operating at dual frequencies of 420 kHz and 1 MHz, is being designed to track individual animals in three dimensions and to provide a synoptic view of small-scale phenomena such as patch morphology and evolution.

The group concluded that an acoustic device, towed from a ship, that would permit mapping of zooplankton throughout the water column was especially desirable for the eastern boundary current - an area of changing and evolving oceanographic features. The design of such a device would have to account for the traditional trade-offs between range as a function of frequency (i.e., higher frequencies=shorter ranges) and the kinds and sizes of animals to be studied. The potential also exists for defining a three-dimensional volume at a fixed locality and surveying the volume repeatedly over time to observe the time-varying evolution of structures within the volume.

Group members also noted that because relatively high frequencies were needed to obtain a back-scattered signal from zooplankton, any correlation with mesoscale features would have to be obtained by a towed acoustical device. Maximal ranges for such devices to see the largest animals (euphausiids) would be no greater than 1 km.

## OPTICS

The group supported the view of Holliday et al. (1991), who highlighted the synergistic relationship between acoustics and optics. Presently, optics is the only remote sensing technique that provides a unique identification of animal species and size. Unfortunately, optics are useful only for an extremely small volume of water - typically with dimensions of several centimeters. But an in situ optical imaging system which could identify animals that were being ensonified could provide ground truth for the acoustic system.

An intriguing possibility, briefly discussed, concerned the many advantages of airborne platforms - ease of deployment, short notice, and the potential for more control of the sampling area with higher resolution. Methods for resolving three-dimensional structure in the surface layers must be developed for such an approach. Futuristic approaches include stereo viewing from two platforms, and laser ranging, which uses time delay to judge distance.

## DATA COLLECTING, PROCESSING, AND ARCHIVING

Clearly, a program encompassing a large variety of devices ranging from moorings to satellites will require diverse data formats. Assimilating these different types of data will present a challenge for the research community.

The need for real-time data was addressed. Both satellite and mooring data are important and could be used to help scientists select survey sites. Dates of a cruise usually become fixed far in advance of departure, but environmental information could be used to determine the exact location for a survey immediately before the cruise. Since the eastern boundary current (EBC) is an area of diverse, ever-changing, oceanographic features, a timely and opportunistic determination of survey locations would be highly advantageous. In addition, satellite information is needed at sea to guide the field studies, since site selection could be partly based on the satellite information. Subsurface events detected from moorings, if available in real time, could also guide fieldwork.

To facilitate the science, it is essential to consider the types of data and the storage techniques that will be used. As a preliminary step, the EBC community should determine whether generally accepted standards exist for storing and processing oceanographic data. Many institutions have already considered this issue. For example, both the University of Miami and the Jet Propulsion Lab have on-line data bases that can obtain data over a network. A recent research initiative funded by the Office of Naval Research deals with new methods for managing data and visualizing oceanographic data. Other research initiatives with similar requirements (such as JGOFS) may develop data-handling methods that could be adopted by the GLOBEC community. The National Center for Atmospheric Research (NCAR) may also have data-handling techniques that could be used. Finally, the 40-year CalCOFI data base should be considered to ensure compatibility.

The group discussed the advantages and disadvantages of central and distributed data storage. With the advent of high-speed computing networks, it is possible to store and retrieve relatively large amounts of data across networks. This would warrant a distributed network in which individual scientists are responsible for their own data, but allow access to other members of the community. This system has the advantage of allocating more funding to individual investigators but requires greater coordination. The creation of a central data facility would reduce the funds available for research but could have the advantage of a small staff to assist users, thus ensuring that the data would be available to both naive and sophisticated users, and that necessary preprocessing would be responsibly handled. Other schemes that combine both of these options are also possible.

## WISH LIST

The following instrumentation needs, not met by existing or newly planned instrumentation, could be considered in a proposal request.

- A new tool for paleo-oceanographers, to ensure that cores are not ruined when drilled in methane-rich environments
- A four-dimensional (3-space + time) tracker to give information about currents
- A sampling device to permit monitoring a patch of zooplankton over time (i.e., a patch-following instrument, conceivably imitating behavior as well as advection and dispersion)
- A turbulence probe
- A concurrent video imaging system to look at particles that are being imaged acoustically
- A profiling mooring - a device that moves up and down in the water column either at a fixed location or in a drifting mode to sample a continuous profile
- A system capable of obtaining three-dimensional optical data from airborne platforms; that is, to measure variables as a function of depth as well as of latitude and longitude

## DEVELOPMENT AND USE OF BIOTECHNOLOGICAL TOOLS

Biotechnological tools offer a wide variety of techniques for analyzing specific classes of organic molecules, particularly those making up or closely controlled by an organism 's genetic identity. Many questions of central importance to GLOBEC can be addressed only with biotechnological tools, or can be answered more efficiently with such tools than by more classical methods, or can be answered on spatial or temporal scales at which classical methods are inadequate.

Such techniques can be used in at least two basic ways: (1) To identify species and subpopulations. GLOBEC is concerned with changes in abundance and distribution of marine populations; thus correctly and efficiently identifying such units is critical. A related use is in identifying body parts or other remains in guts of predators (to determine diets) or in sediments. (2) For proxy measures of physiological or reproductive states (e.g., age, sexual maturation) or of individual metabolic rates (e.g., ingestion, respiration) or demographic rates (e.g., natality). Knowledge of states can reveal responses to sublethal stresses, or facilitate the assignment of critical events, such as first reproduction, to a specific age. Metabolic rates are used to calculate material balances (income minus outgo of organic matter), which can lead to changes in populations, and demographic rates permit the direct calculation of such changes.

The above measurements are needed in all GLOBEC regions of study, and are not specific to eastern boundary currents. But identifying organic remains in anoxic sediments is more critical in the California Current system than in regions without a usable sedimentary record. Particularly important are techniques robust and sensitive enough to be applied to small amounts of material (micrograms) and to historical collections preserved for other purposes (e.g., in Formalin or alcohol), because past environmental events could be analyzed, and present collections of material simplified.

A wide range of biotechnical tools exists, and many more tools are being developed (though generally for nonoceanographic purposes); the field is evolving rapidly. In choosing techniques, researchers must recognize that the number of samples to be analyzed for any question on the GLOBEC scale will range from at least hundreds to many thousands, so the cost in time and money per analysis must be fairly low. Some present techniques may meet all the requirements, most notably analysis of mitochondrial and nuclear DNA amplified by the polymerase chain reaction to determine genetic identity. More tools must be developed, and existing ones need to be further calibrated, for different organisms, so that interpretations are more exact. but several techniques are ready to be applied to GLOBEC studies.

GLOBEC issued a request for proposals (RFP) in biotechnology and funded two projects for assessing metabolic health. The RFP, in the opinion of the committee, correctly and fully identified GLOBEC's needs. The group recommends that, rather than designing new criteria, GLOBEC should rerelease the same basic RFP, backed up with funds to support additional biotechnological projects.

## POLICY ISSUES

The group discussed several policy issues that affect the applications of technology in GLOBEC. The way proposals for sea-going research are prepared and reviewed in NSF has a potentially stifling influence on the development and wide acquisition of technological tools. The cost of ship time is not a line item in the budget of a research proposal, but the cost of a new tool usually is. Therefore some solutions that would be cost-effective in substituting tools for ship time, or in making use of ship time already funded elsewhere, may not be proposed because of the way they affect the budget of an individual proposal. This situation has been discussed many times, within and outside of NSF, and mechanisms exist for developing and purchasing expensive equipment, but even if the problem is only one of perception, it must he considered .

The issue of using ships of opportunity (or other platforms, such as drilling rigs) within GLOBEC was not discussed specifically, although one of the major time series in biological oceanography - the continuous plankton recorder survey of the eastern North Atlantic - was constructed for such use. Proposals exist to greatly expand this approach to monitor the biological marine environment.

A related question is whether the diverse (and diffuse) needs of biologists, their technological innocence, or their relatively modest per capita funding has prevented the formation of a group large enough to support an expensive communal instrument. Some technologies (acoustic Doppler current profilers and bottom swath-mapping seabeams) have become institutionally purchased equipment, supplied with the ship an investigator uses. Some of the more elaborate tools recommended in this report may have to be managed and financed in this way.

### 3.6.2. The Role of Models in the Study of Eastern Boundary Current Systems

Chair: L. Walstad

Participants: B. Hickey, B. Jones, P. Smith, and D. Ware

We recommend that a suite of ecosystem models for the California Current system be developed and that studies of these model systems begin. A number of considerations affecting the form and function of these models are outlined here, and a subset of needed studies is discussed.

The long-term goal is to understand and predict the effect of climate change upon eastern boundary current marine ecosystems. To reach this goal, the initial emphasis should be on understanding the dynamics of model ecosystems rather than on re-creating oceanic ecosystems. Models must include ecosystems as well as specific biological and physical interactions. Coordination between model developers should be required to ensure that components are interchangeable where appropriate. This should lead to more robust models and substantially increase the probability of attaining our long-term goal. As our understanding improves, the models can be modified to more closely reproduce the marine ecosystem.

#### ECOSYSTEM EQUATIONS: CHOICE OF VARIABLES

Although an ecosystem comprises individual organisms, description of a full system at the level of the individual is not expected to be feasible in the near future. Rather, an aggregate measure of the population will be required. Historically, models have used nitrogen or carbon as the quantitative measure of subpopulations within the ecosystem. Promising alternatives include the use of more than one quantitative measure and the use of different measures at separate trophic levels. It should be emphasized that the variables in such ecosystems are amalgamations of similar species and that the particular quantitative measures are simply a means of counting the organisms. Multiple measures may be useful in situations where the C/N ratio varies or where the behavior or response of organisms cannot be related to the biomass alone. Fundamental to the strategy is the premise that the importance of a unit of carbon will depend upon where it is located in the ecosystem. Within trophic levels, subdivisions by body size or functional group may be necessary or desirable.

Table 2 lists potential biological variables for a model of upper-water-column interactions within the California Current system. The phytoplankton trophic level forms the base of the food chain and, through interaction with the water column's physical structure and nutrients sets the overall input of organic matter. A primary focus of GLOBEC research will be on secondary production and zooplankton population dynamics. To understand the variations of important individual zooplankton taxa it is necessary to include them explicitly. We suggest at least four groups representing major but distinctive components of the California Current zooplankton biomass.

Fish populations will also be studied in GLOBEC. The "fish" subdivisions in Table 2 were chosen for their societal importance and because each exemplifies a different migratory or reproductive strategy, or behavior, or feeding pattern. In particular, hake, anchovies, and sardines make up a substantial fraction of the fish biomass in the California Current system and are representative of closely related species that are important in all major eastern boundary current systems. Hake also feed preferentially upon euphausiids and consume much of the productivity of the euphausiid community. Recruitment success in hake and sardine is affected by the availability of suitable spawning habitat and small zooplankton, both of which are affected by upwelling. In addition, the survival rate of some fish larvae may depend upon the availability of specific phytoplankton taxa, so subdivisions of the phytoplankton trophic level may be needed.

Even this relatively complicated trophic and taxonomic subdivision of the population may not be sufficient; in some cases specific age classes or identifiable genetic pools within fish and zooplankton species may be needed. Also, the zooplankton community may have to be further divided according to body size or reproductive pattern. Meroplanktonic larvae and their benthic adult stages may also have to be included for some GLOBEC research objectives.

Rates of the fundamental life processes are also needed to complete the model. For each variable, uptake (as fixation or consumption of organic matter), excretion, recruitment, death rates, and (in some cases) migratory and reproductive strategies must be provided.

Table 2. An Example of Trophic Subdivisions

| Fish* | Zooplankton | Phytoplankton | Nutrients |
|---|---|---|---|
| Hake (8) | Euphausiids | Dinoflagellates | Nitrate |
| Anchovies (3) | Copepods | Diatoms | Carbon |
| Sardines ( 1-2) | Salps | | |
| Mackerel (1-2) | Microzooplankton | | |

*Numbers in parentheses indicate the potential number of year classes.

## REQUIREMENTS FOR NEW OR ADDITIONAL MODEL INPUT

Extensive research has already been carried out for most of the suggested biomass pools and some of the required rates (e.g., Francis 1983; Livingston 1983; Tanasichuk et al. 1991), as have model studies of pieces of this or similar ecosystems (Walsh 1975; Wroblewski 1977, 1980, 1982). Similar field, laboratory, and modeling studies will be needed to identify the remaining rates and the dependence of these rates on the physical and biological environment. Identifying how key rates and strategies depend on physical variables (e.g., stratification, temperature, turbulence) that may vary with climate change is particularly important for GLOBEC.

Horizontal and vertical migration at the higher trophic levels pose an especially difficult modeling task. Fish, which migrate a significant horizontal distance and appear to select spawning sites, must be represented by models that include migratory and spawning parameterizations. These parameterizations will contribute to the horizontal redistribution of fish through specification of swimming rate and direction. Identification of spawning regions is also important because these regions represent sources for larval stages and thereby determine the distribution of juvenile fish.

Physical models are needed to provide three-dimensional fields of temperature, salinity, velocity, and turbulence. Fish eggs and larvae and the lower trophic levels will be advected through these fields, and uptake, excretion, and survival rates will vary, partly as a function of local physical conditions. Larger fish tend to be more independent of these fields, except for spawning, which is closely coupled to upper-ocean temperature distribution. But larger fish may be indirectly coupled through their food supply. For example, the spatial and trophic association of hake with the euphausiid stocks that are abundant along the upwelling front suggests that hake populations may be influenced by the physical dynamics of the upwelling front. A goal of the physical ocean models should be to reproduce the gross features of the upwelling front, including seasonal and alongshore distribution of upwelling, the local upwelling rate, and the persistence of the front.

Daily cycles of atmospheric forcing, and the ocean's response to this forcing may be important. These cycles include intensification of alongshore winds off northern California, and set-up of sea breeze. Alongshore winds are critical for correctly reproducing the upwelling. The set-up of the sea breeze and resulting increase in turbulent forcing of the upper ocean may significantly affect the plankton community by increasing the turnover rate within the mixed layer or deepening the mixed layer at the time of day when photo-inhibition would affect phytoplankton confined to the upper few meters. Although physical models are improving in their capacity to reproduce mixed-layer cycling, depth, and turbulent intensity, a continuing effort will be required.

Sensitivity studies and scaling of proposed model systems should begin as soon as possible. Sensitivity studies may be used to help rank the importance of components of the observational plan, but only if sufficient lead time is provided. Studies should address the form of uptake rates at each trophic level and should characterize the system's sensitivity to changes in total biomass or increased interannual variability. Because this is a nonlinear system, chaotic behavior should be investigated with the predictability of the system in mind. It is likely that some aspect of the system will be sensitive to initial or boundary conditions or to parameter choices; however, some quantities may prove to be well predicted. Quantities of interest - zooplankton biomass, for example - should be determined and examined for predictability. Scaling of the system of equations may reveal fundamental balances that can be used to define the system's basic dynamics. The physical oceanographic analogues of this process include the derivation of quasi-geostrophy, Ekman balance, and wind-driven and thermohaline circulation theories. These early studies will necessarily be simple, but the experience gained will lead to better understanding in the future and may help improve the field program. In several areas (listed below) we recommend, based on present information, focused sampling and special-purpose submodels of particular ecosystem features or components.

Biological patches - both their biological consequences and the appropriate methods for including them in ecosystem models - are not adequately understood. Theoretically, the importance of spatial heterogeneity is attributed to nonlinear coupling of ecosystem components. Field sampling on fine horizontal and vertical scales will be important to understanding patch phenomena. Also, model studies of small regions on fine horizontal scales may help determine how to include the effects of patches in models with coarser spatial resolution.

Because the ecosystem comprises individuals, the most direct means for reproducing ecosystem behavior would seem to be through modeling of individuals. Current laboratory studies should yield improved quantitative descriptions of individual behavior (e.g., predator-prey interaction). Studies of small ocean regions with models that can track the position of 'individuals" (Hofmann et al. 1991) might improve parameterizations in biomass models focused on larger scales. Improvement and application of these individual models should be encouraged, especially when the emphasis is on improving biomass models.

Various kinds of historical data provide a basis for validating model response to a wide range of climatic forcing. The paleo-oceanographic record in the California Current system is the subject of a separate working group. But we note here that individuals of long lived-species (e.g., *Sebastes* spp.) can provide up to a 100-year record of their growth pattern. Many of these species show considerable territorial fidelity and thereby provide a proxy record of local environmental conditions.

## SUMMARY

An eastern boundary current model suite is needed to further our understanding of the marine ecosystem. The long-term goal is a model that reproduces the behavior of the ecosystem, including the response to climate change. An appropriate set of equations has not yet been put forth, but considerable field and laboratory and model-subsystem studies have been conducted. A preliminary suite of models should be developed and adopted, and sensitivity experiments should be conducted. This is an ambitious goal, but the process of developing ecosystems models is likely to identify needed studies as well as to focus some aspects of the field program. Because of the system's complexity, such a model is expected to comprise multiple trophic levels with subdivisions in each level. The initial objective should be to understand the dynamics of this model system rather than to reproduce the marine ecosystem. As field and laboratory studies develop, our

understanding of the ecosystem will be corrected at the process level. All components - including the physical model, patch dynamics, physiological rates, migration pattems, and spawning patterns - will need considerable development.

### 3.7 Linkage of Observation Programs at Different Time and Space Scales

Cochairs: A. Huyer and L. Botsford

Participants: T. Baumgartner, R. Francis, B. Jones, C. Miller, J. Paduan, L. Rosenfeld, T. Strub, D. Ware, and L. Washburn

The problem of studying the response of the California Current ecosystem to climate change is one of sampling - over a long period, with high temporal and spatial resolution - a large, three-dimensional volume with many habitats, and many species mixed together from several sources. With finite resources, it is impossible to sample all of the species in the entire domain frequently enough for a long period. Therefore, we must carefully design our sampling of target species and spatial and temporal scales to maximize information about this ecosystem.

The goal of this part of the GLOBEC program is to understand how an eastern boundary current ecosystem (the California Current system) responds to climate change, which involves a number of different time scales. Ultimately, we want to describe slow or abrupt but infrequent changes on long (climatic) time scales. In practice, however, we must collect information over a fairly short interval (perhaps five years, initially). In designing these initial studies, we cannot attempt to monitor or directly observe the impact of long-term climate change. Thus, we must focus on understanding present fluctuations well enough to predict changes caused by projected changes in climate (e.g., changes in wind fields, frequency of ENSO events, etc.) .

Time and space scales also affect the choice of target species. Since the link to climate change involves long time scales, we can gain substantially by choosing species with long historical data bases, such as catch statistics and, especially, a paleorecord from sediment data. Another strategy to maximize the information gained is to choose species for which we already have information about potential physical influences. This will allow us to begin testing hypotheses about critical dependencies of certain life stages on the environment, rather than spending time discovering these dependencies from scratch. A long-term goal of this GLOBEC study would be to identify species that could be monitored indefinitely to indicate the health of the ecosystem over time.

The California Current system encompasses a wide range of spatial scales. The narrow region over the shelf (within 10 to 30 km of the coast) is particularly important for recruitment of juveniles of shelf species, since larvae that are carried farther offshore must return to this region to survive. The region within and offshore of the Southern California Bight is important, because species such as hake spawn only in this area, but range over the entire system during relatively long lives (5-20 years). At the largest scale (see Section 3.1), this report has identified three major north-south regions: a northern region off Vancouver Island, Washington, and the northern half of Oregon; a central region from Cape Blanco (43°N) to Point Conception (35°N); and a southern region within and offshore of the Southern California Bight. The area off Baja California constitutes a fourth north-south region, which we hope will be included in the final research design through cooperation with Mexican scientists. Each of these regions contains at least three domains in the offshore direction: the coastal domain (within several hundred meters of shore); the shelf domain (within 10 to 30 km of shore); and the offshore domain over the deeper ocean (between the shelf break and roughly 500 km offshore). In principle, each of these north-south and offshore regions should be sampled, although resources may limit this in practice. Satellite observations should be used for a synoptic overview of the large-scale system, which will provide the context for the more localized, in situ data. Several types of observational programs, lasting from 5 to 30 years, should be carried out.

## INTENSIVE STUDIES

We envision several intensive process studies of the ecosystem covering time scales of hours to months; space scales of a few centimeters to hundreds of kilometers; and organisms from the lowest to the highest trophic levels, including phytoplankton, zooplankton (e.g., euphausiids and copepods), fish (anchovy, sardine, and hake), and meroplanktonic benthic organisms (e.g., Dungeness crab and sea urchins). Because target species with different life histories span different space and time scales, physical variables must be measured on the scales appropriate to each organism. Intensive studies will employ a wide variety of physical techniques including drifters, moorings, ROVs and AUVs, surveys, microstructure observations, etc. They will also employ traditional and innovative techniques to measure biological processes and populations.

Satellite data will also be useful for the intensive studies. The most biologically important satellite sensors are those that measure ocean color, and the only presently funded satellite mission dedicated specifically to ocean color will be the SeaWiFS mission during 1993-98. A follow-on SeaWIFS satellite is being planned for launch in 1998 under EOS funding; this should provide good color data for the next ten years. Other planned ocean-color sensors have a poorer signal-to-noise ratio and orbits that are less optimal for color (West Coast passes will be earlier in the morning). Thus, to take advantage of the most certain, high-quality satellite color data, some intensive studies should be conducted within the 1993-98 period.

## MONITORING TIME SERIES

To link the intensive studies together over longer time periods, we recommend long-term monitoring. This will include coastal stations, nearshore and offshore buoys, and subsurface moorings.

Coastal stations: solar radiation, wind speed and direction, atmospheric pressure, air and water temperature, air humidity, salinity, and sea-surface elevation should be measured continuously at coastal stations for at least 20 years.

Nearshore and offshore buoys: solar radiation, wind speed and direction, atmospheric pressure, sea-surface elevation, air and water temperature, air humidity, upper-ocean velocities and temperatures, salinity, wave height and period, fluorescence, etc., should be measured continuously at a few nearshore (1-10 km offshore) and offshore (100-200 km offshore) buoys for about 20 years.

Subsurface moorings: water temperature, salinity, velocity, fluorescence, nutrients, light transmission, solar radiation, zooplankton biomass (estimated acoustically), and organic particulate flux (into sediment traps) should be measured continuously for more than 10 years at six sites: nearshore and offshore in the northern (>43°N), central, and southern (<35°N) domains of the California Current.

All time-series data should be available in real time (to the extent feasible) so that opportunistic studies can be conducted within a known background.

Regular cruises will be needed to provide calibration and in situ measurements of particular parameters, and also to determine the local spatial structure around the monitoring sites. For example, which species contribute to zooplankton biomass? What is the relationship of plankton species in the water column to those sampled by sediment traps?

In addition to the open-water mooring sites, an estuary or embayment in each of the three California Current domains (northern, central, and southern) should be used to monitor target species that depend on nearshore estuarine habitat.

Satellite data (AVHRR, color, altimeter, and offshore scatterometer) and ships of opportunity should be used to monitor large-scale, low-frequency variations of the California Current. Satellites, however, can sense only the upper ocean; ongoing field studies will be required to relate the surface layer to the deeper ocean.

To augment new data, historic data sources should yield information on low-frequency variability. Even such widely used sources as CalCOFI and COADS (Comprehensive Ocean Atmosphere Data Set) still contain information that has not been fully exploited for understanding ecosystem processes. Newly compiled data sets such as those assembled as part of the ongoing Pacific Climate Workshop (Cayan et al. 1991) should provide new insights into the system on time scales of a hundred years and less. The longest time series are from anaerobic sediments, which provide records longer than a thousand years and can resolve variability on scales of years to several decades. Thus, at the monitoring sites it is important to collect data that facilitate linkage to these longer data sets; for example, sediment traps should be included in the mix of instruments.

## OPPORTUNISTIC PROCESS STUDIES

A useful adjunct to long-term monitoring will be opportunistic process studies, which will allow us to focus efforts on areas and times of interest. These studies should be conducted when the monitoring time series indicate either that physical conditions are unusual (e.g., ENSO), or that specific or unusual biological events are occurring (e.g., spawning, an unusually large phytoplankton bloom, etc.). To make such studies possible, we need flexibility in ship schedules; perhaps one ship per institution should be assigned to the project for an extended period (e.g., 2-3 years). Some opportunistic studies (e.g., drifter deployments) can be conducted from aircraft, whose schedules are generally more flexible; others could use ROVs or AUVs. Such studies would be designed on the basis of available satellite data, monitoring time series, and other relevant data.

## MODELING

A useful way to connect information on short time and space scales with information on long scales, in terms of biological significance, is through models that span several levels of organization. Typically, processes on short time and space scales influence behavior and survival of individuals, whereas longer scales are relevant for populations, communities, and ecosystems. Models that explicitly include life-history rates of individuals and connect them to higher levels of organization (i.e. ,population, community, ecosystem) can significantly link studies on different scales.

## DATA MANAGEMENT AND EXCHANGE

For linkages between studies of different time and space scales, it is essential that we promote uniform data management and rapid exchange. Formats for data and data exchange should be specified as early as possible: before the experiment begins for traditional parameters (T, S, velocity, etc.), and after initial testing for newly measured parameters. Access to all data is critical to the study of ecosystem processes. Data sharing and priority rights should be spelled out before a project begins; in all cases, the data should be widely accessible as soon as the initial manuscript is submitted for publication, or sooner. New and established techniques for displaying and visualizing data through interpolation and modeling should be used to make the observations readily accessible to all investigators.

## 3.8 Major Shifts in Species Composition and Ecosystem Structure

Cochairs: A. MacCall and P. Kremer

Participants: W. Graham, R. Haney, A. Hollowed, D. Mackas, M. Ohman, T. Powell, G. Rau, J. Rice, J. Schumacher, L. Shapiro, P. Smith, L. Welling, and E. Woehler

## PROBLEM DEFINITION

Time series of physical and biological measurements in eastern boundary currents (if not in the oceans in general) exhibit nonstationary properties: abrupt changes in descriptive parameters such as mean, variance, or phase relationships that are seemingly unpredictable and inconsistent with those from a preceding time period. Isaacs (1976), who referred to qualitative states as "regimes," described this problem as follows: "There are internal, interactive episodes locked into persistence, and one is entirely fooled if one takes one of these short intervals of a decade or so and decides there is some sort of simple probability associated with it....fluctuations of populations must be related to these very large alternations of conditions."

Qualitative shifts in physical properties, species composition, and ecosystem structure may exist on a variety of spatial and temporal scales, but in the California Current they are most obvious in long-term records of temperature and fish abundance. The historical temperature record from the Scripps Pier shows three prolonged periods of different mean annual temperature (Fig. 10). The middle period, extending from the early 1940s to the mid 1970s, is so much colder than the adjacent warm periods that the warmest years during the middle period (with the exception of the 1958-59 El Niño) are all below the average temperature of the warmer periods (MacCall and Prager 1988). Although the Scripps Pier record is local, SST observations from ships show the recent warming to encompass the entire northeastern Pacific rim, from the equator to the Aleutian Islands (Fig. 11). Again, the lack of cold anomalies since 1976 is striking. From an ecosystem perspective, temperature is only an easily measured proxy variable, and is related to a suite of physical conditions that in turn influence biological processes. Major biological shifts in the California Current ecosystem have been documented for the recent warm period, including a drop in zooplankton abundance and vigorous recovery of the previously depleted Pacific sardine (Barnes et al. 1992).

Despite our recognition that time series of physical and biological oceanographic variables often exhibit nonstationary properties, this concept is overlooked in actual practice. In many cases, nonstationary or qualitative shifts are ignored in order to simplify models to a tractable level. This is especially the case where spatial and temporal coverage are limited. Ambitious large-scale observation and modeling programs such as the World Ocean Circulation Experiment (WOCE) are necessarily still at the level of describing a single pattern of ocean circulation. Similarly, applied models of biological productivity, such as fishery management and marine mammal population models, are typically based on simplifying assumptions of constant reference points such as equilibrium-unexploited abundance.

## RELEVANCE TO THE CALIFORNIA CURRENT SYSTEM

The number of historically observed transitions is small, but it is reasonable to infer that qualitative shifts in state are typical of the California Current system and that they will continue to occur every few decades. Qualitative shifts in this and other eastern boundary currents pose a suite of challenging problems (Lluch-Belda et al. 1989).

## SYSTEM UNDERSTANDING

Although the California Current is one of the best-studied regions of the world's oceans, our present understanding of its physical and biological oceanography is inadequate to explain or predict the qualitative shifts we have observed. With the exception of El Niño, these shifts have been overlooked, probably because studies have not included appropriate time and space scales to approach the problem quantitatively. Recent developments in the mathematics of dynamical systems (e.g., "chaos")have demonstrated that qualitative-state shifts can arise from rather simple nonlinear models (e.g., May 1986). With this realization, augmented by a new kit of conceptual "tools", the problem of qualitative shifts is now emerging as a legitimate and fundamentally important area of oceanographic investigation.

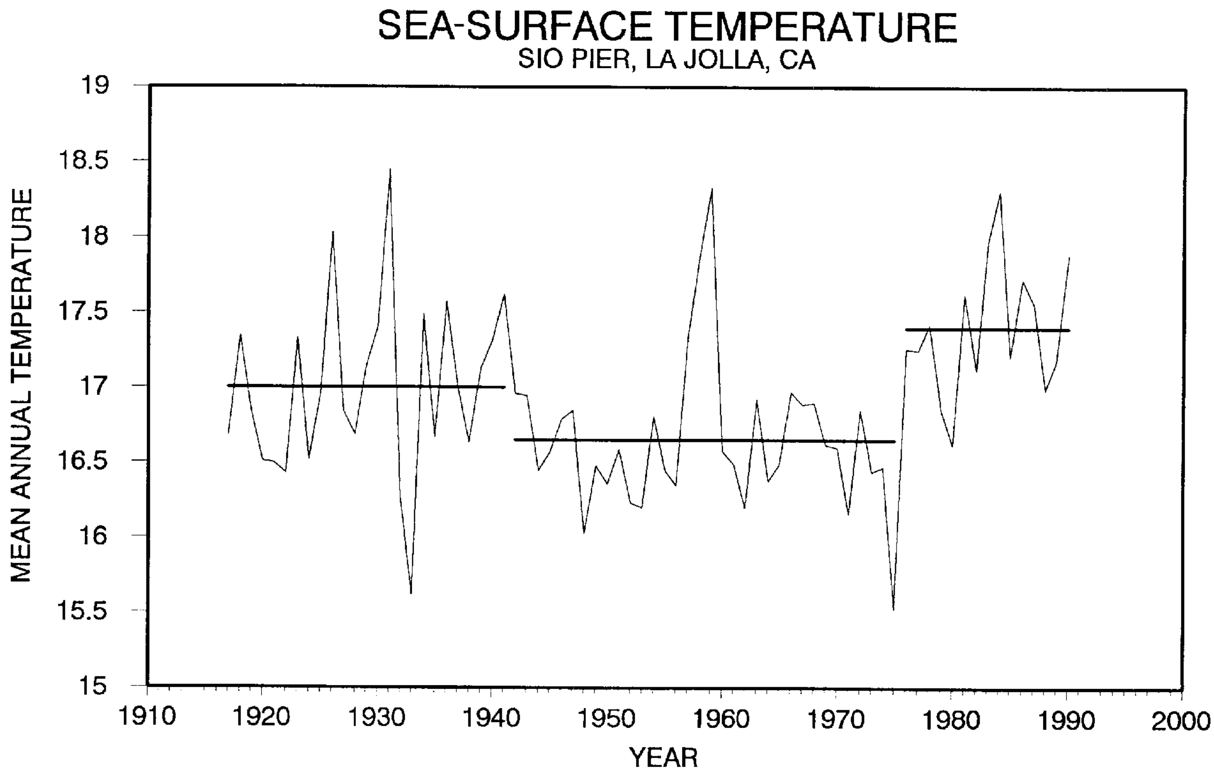


Figure 10. Mean annual sea-surface temperatures observed at Scripps Pier, La Jolla, California. Long-term averages are shown for three qualitatively different periods.

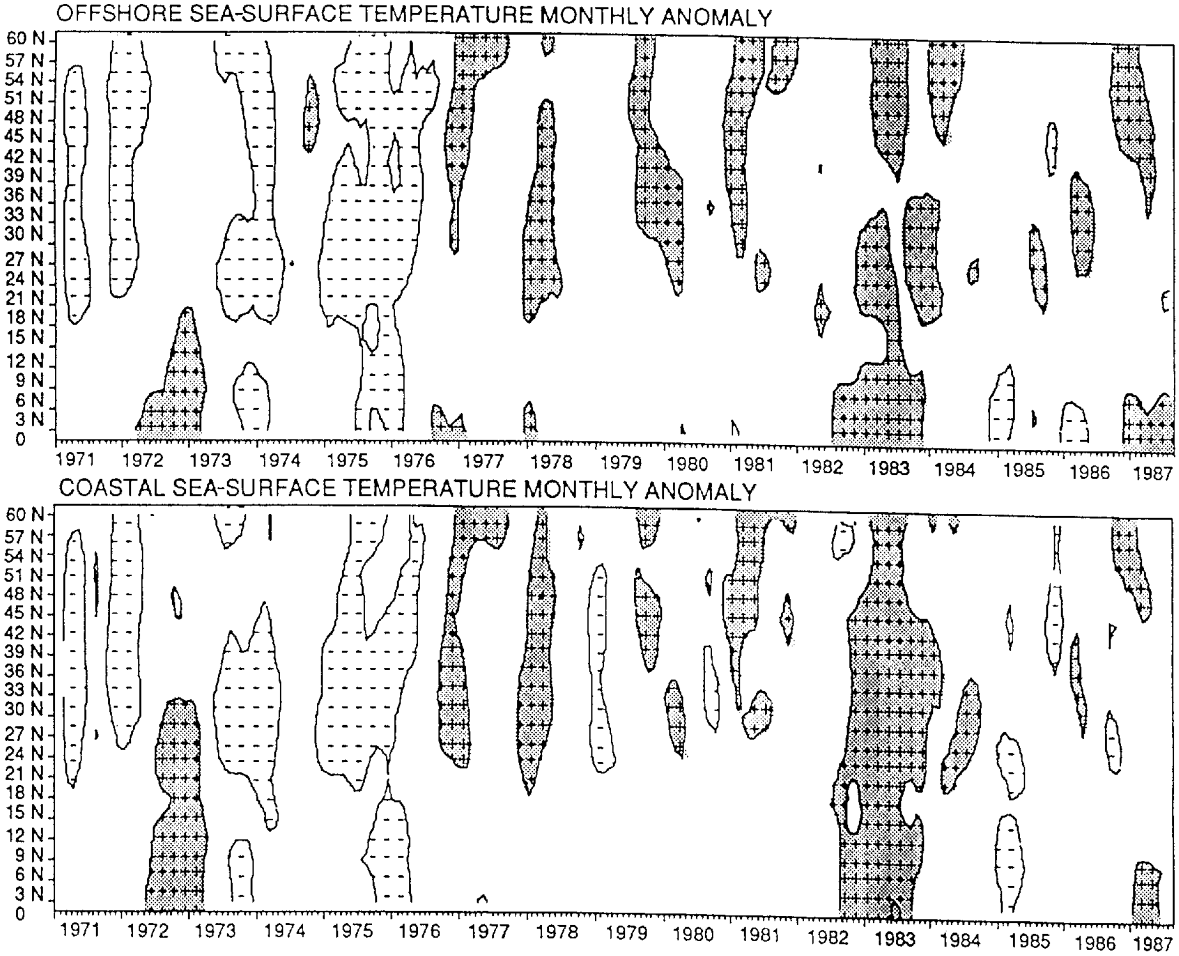


Figure 11. Anomaly of monthly mean sea-surface temperatures from ships of opportunity (Cole and McLain 1989). Contours are (+/-) 0.5 degrees Celsius, positive anomalies are shaded. "Coastal" is approximately 0 to 200 km from shore; "offshore" is approximately 200 to 600 km from shore.

Although qualitative shifts are most noticeable and best documented at large scales in space and time, there is a spectrum of conceptually related phenomena ranging in size down to much smaller, localized scales. For example, the zooplankton in one parcel of water may be dominated by crustaceans (e.g., copepods and euphausiids) while zooplankton in a nearby parcel may primarily comprise pelagic tunicates (salps and doliolids) . Physical circulation patterns have been documented to be important in determining the spatial distribution of the zooplankton, but we lack appropriate time series measurements to determine the mechanisms that cause qualitative difference in the zooplankton community. Zooplankton species compositions and abundances directly affect fisheries recruitment. The processes leading to localized alternative states may provide insights into mechanisms that are important at longer and larger scales. Although these short-term localized changes are more amenable to direct study than long-term ecosystem shifts, short-term studies should not be viewed as substitutes for long-term investigations. Research on state shifts must necessarily cover the full range of time and space scales.

## RESOURCE MANAGEMENT

Resource management policies that incorporate qualitative shifts in ecosystems have not yet been developed. Models commonly used for managing living marine resources assume a steady state, perhaps with allowance for environmental "noise." On the west coast of North America, this steady state assumption is clearly inappropriate even in the absence of global climate change: qualitative shifts in species composition and structure appear to be a property of the ecosystem. Many resources and industries may be at risk if qualitative ecosystem shifts result in inappropriate management expectations and responses. Eastern boundary currents are known for their spectacular fishery collapses such as those for the Monterey sardine and the Peruvian anchoveta. Such collapses seem to be an inevitable consequence of inadequate understanding of the resources and the ecosystems. The required knowledge consists of (1) improved resource management models based on understanding of qualitative-state shifts; and (2) improved capability to predict state shifts or to recognize them as early as possible after they have occurred. It is doubtful that adverse fluctuations in the stocks and related industries can be avoided, but if management were armed with the above knowledge and acted appropriately, it should be possible to reduce the severity and duration of the downturns and their resultant economic and social hardships.

## GLOBAL CHANGE

Qualitative shifts in ecosystem state occur normally. Although there is no assurance that past states will recur under conditions of global warming, past ecosystem behavior is still our best source of clues about future states and dynamics. Logical induction leads us to the hypothesis that, at least in the California Current system, physical and ecosystem response to global change (whether or not the change is anthropogenically forced) may consist of abrupt changes in qualitative states (e.g., a step function) rather than the gradual change suggested by the smooth forcing function of increasing atmospheric greenhouse gases.

This possibility has profound implications not only for timely detection of the effects of global climate change, but also for planning appropriate societal responses. Therefore, investigations of the response of eastern boundary currents to global climate change must be designed to encompass these changes. We have referred to state shifts as "qualitative," because of their most noticeable properties, but it is nonetheless essential to describe and understand these phenomena quantitatively. GLOBEC-sponsored research on qualitative shifts will provide the understanding necessary to fully consider the effects of global climate change on the California Current system and similar eastern boundary currents.

## KEY RESEARCH QUESTIONS

- What controls the shift from one qualitative state to another? To what extent are qualitative shifts predictable? What are the time and space scales of these shifts and their transitions? What ecosystem properties are conserved across state shifts? Are the mechanisms initiating the shift different from those maintaining the state within a qualitative regime?

- What are the relationships and linkages between physics and biology in causing and maintaining qualitative shifts? Do changed physical conditions force a specific ecological response, or do they allow a suite of possible responses? What generates hemispheric-scale shifts in physical and biological systems? How do seemingly small differences in properties or histories of water masses result in large differences in the biological communities inhabiting them? What is the relationship between changes in space and changes over time? How can we better distinguish between advective processes and in situ dynamics?

- What is the significance of initial conditions? Are the characteristics of qualitative shifts determined by initial conditions, or is the end state independent of those conditions? What is the importance of " seed " populations?

- What are comparative life-history strategies of species or populations impacted by qualitative shifts? Do endemic species respond differently from more widespread species? Are there large-scale trophic consequences to local shifts in invertebrate populations?

- At what point in time (or space) are qualitative shifts identifiable, and how much change is required to constitute a shift? Are there characteristic physical or biological precursors? Are there convenient proxy variables for monitoring system status and early detection of shifts? What are appropriate management strategies for harvested or conserved living resources - strategies that recognize the frequency and impact of qualitative shifts? What are appropriate management (and research) responses if a shift is believed to be imminent?

## PROPOSED PROGRAM: EXAMINATION OF HISTORICAL AND PALEOSEDIMENTARY DATA

Long time series of physical and biological observations exist from a number of sources for the California Current system (CCS) . CalCOFI samples of fish larvae and larger zooplankton constitute a detailed 40-year time series (1951-91) for a major portion of the CCS. Catch records of commercially important fish have been kept for 75 years. Paleosedimentary records from anoxic basins provide data essential for documenting qualitative shifts on the time scale of decades and longer (see Section 3.3). In addition to directly examining material preserved in sediments, we need to identify proxy variables that reliably indicate physical and biological conditions.

Analyses of historical data will provide the basis for identifying shifts in ecosystem structure and suggest hypotheses for mechanisms or processes that may govern these shifts. These hypotheses can be tested within the context of the modeling and field effort or by comparing results with historical data not used previously to generate the hypotheses (e.g., cross-validation). They can also be validated or invalidated by future monitoring efforts.

## MODELING APPROACHES

The working group advocates two complementary, converging lines of modeling: process-oriented models and process-neutral models. Process-oriented models are particularly appropriate where processes are relatively well understood, as in physical oceanography. However, effects of some relatively well-known physical processes such as wind-induced turbulence may be better modeled by a "process-neutral" transfer function (wind speed cubed), which concisely describes the results of the process without explicitly modeling the process itself (surface wave dynamics, etc.). When less-well-understood processes must be included in a larger model, process-neutral models may be required. These may be drawn from a large family of models including probabilistic models (e.g., Markov models) and empirical transfer functions that may be nonlinear and incorporate appropriate time delays.

These process-neutral models form a natural beginning point for the evolution of more specific models tailored to the processes and mechanisms of the California Current. Process-oriented models follow naturally from neutral models as more information is gained . The process-oriented model then becomes available to replace the process-neutral model, depending on the modeling context. Ideally, interaction between construction and analysis of models and conduct of field research strengthens investigations in both areas.

## PHYSICAL OCEANOGRAPHY

Ecosystem shifts appear to be closely associated with changes in physical conditions. Better knowledge of the physical processes and characteristics of alternative system states is needed in the field of physical oceanography. Such knowledge would clearly help to explain qualitative shifts in the biology of the system. Improved circulation models (including patterns and effects of upwelling, advection, and transport) are needed. Beyond describing "average" conditions (the significance of which becomes questionable in view of nonstationarity and discontinuous qualitative shifts), we need descriptions of alternative physical states, and knowledge of mechanisms or processes that generate shifts between (and persistence within) those alternative states.

## BIOLOGICAL MODELS

Biological systems are laden with many properties that applied mathematics has shown to generate complicated temporal and spatial behavior, and the phenomenon of qualitative biological shifts is a natural consequence. Some examples of these properties are nonlinear responses to physical and biological changes of the sorts often encountered in the recently developed field of "dynamical systems"; plasticity in trophic relationships among species (especially given individual development from larva through adult, spanning numerous trophic levels); effects of time lags; and continuous spatial (re)partitioning of populations. A mix of process-oriented and process-neutral models is necessary, and that mix will evolve with improved understanding.

Stability properties of ecosystems may arise from specific processes or mechanisms, but alternatively could arise from more general properties of the component physics, organisms, and ecological linkages. In the latter case, process-neutral models may guide subsequent research in several ways, including identification of dependencies that are likely to constrain system trajectories or maintain alternative states; identification of stable and unstable assemblages or configurations of the ecosystem; and determination of model sensitivity to assumed structure or parameter values.

## FIELD STUDIES

Initially, field studies will concentrate on mechanisms governing qualitative-state shifts in systems small enough that transitions can be observed. This research would concentrate on many of the key questions listed above (e.g., predictability of qualitative shifts, comparative life histories of species, physical and biological precursors). The study of long-term qualitative shifts must rely on historical records, archived samples, and proxy or indicator variables. Efforts to model qualitative-state shifts will identify numerous features and processes requiring clarification and better understanding through field study, including identification of critical mechanisms or sensitive leverage points, and estimation of parameter values for use in models of key processes. Identification of specific areas of study is premature, but an ambitious GLOBEC field program is likely to result. Increased field activity should be anticipated as the program develops, and funding should vary accordingly.

## PRODUCTS

Understanding the mechanisms and causes of long-term qualitative shifts in the California Current ecosystem poses a major intellectual challenge. If we are successful, our knowledge will provide a basis for monitoring and forecasting that would clearly benefit society. Even if prediction proves unfeasible, earlier recognition of qualitative shifts would also be beneficial. Therefore, a major product of this proposed GLOBEC research program is the development of a physical and biological diagnostic capability that could be implemented by an agency such as NOAA

The proposed prediction and detection capability would be supported by a low-cost monitoring program. Design of that program will follow the research conducted under this GLOBEC program, but some aspects can be anticipated: presumably, existing climatological observation sets (e.g., information from ships of opportunity and coastal stations, atmospheric pressure fields) would be emphasized. A variety of satellite-based sensors may be expected to provide synoptic views of some variables of the coastal ecosystem. These could be supplemented by low-cost opportunistic biological samplers such as Hardy Continuous Plankton Recorders to obtain detailed information about shifts in species composition and distribution of zooplankton, with emphasis on possible indicator species. Other indicators of shifts (recruitment strengths, growth rates, physiological traits) may be extracted from routine biological monitoring of commercial fisheries at little incremental cost to ongoing sampling programs.

The combined monitoring and analysis could produce indexes of environmental indicators analogous to those published by the Department of Commerce for the U.S. economy. NOAA has already moved in this direction by initiating an annual compendium of environmental indicators. The program described here differs from the NOAA effort in two important ways. First, the indexes would be restricted to a better-defined system: the California Current off the west coast of the United States and Canada. Second, the indexes would be better focused, having been developed and selected on the basis of mechanisms and relationships identified by the research program.

The California Current is an ideal laboratory for developing such a predictive system. The background of knowledge and historical observations is among the best in the world, and provides a solid base from which to work. Successful effort in this system will point the way for similar programs in other coastal and oceanic systems.

## 4 ACKNOWLEDGMENTS

We thank the staff of the Bodega Marine Laboratory (BML), and in particular Dennis Hedgecock and James Clegg, BML director, for providing the venue of this workshop. Very special and individual thanks go to Vicki Milam of BML for her many on-site efforts to organize facilities and schedules, and to Diane Foster of the Southwest Fisheries Science Center for compiling the ever-volatile list of attendees and the subsequent iterations of the workshop report. We also thank Julie Olfe of La Jolla for technical editing of the final report, and Ron Tipper and Allison Burns of the Joint Oceanographic Institutions for their advice and help with meeting and report preparation. Mark Ohman and Jake Rice ensonified the meeting with their version and rendition of "The Jets Song: West Side Story." Lyrics (they're good) are available on request from the workshop cochairs.

# 5 LIST OF ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| ADEOS | Advanced Earth Observing Satellite |
| AUV | Autonomous Underwater Vehicle |
| AVHRR | Advanced Very-High-Resolution Radiometer |
| BML | Bodega Marine Laboratory |
| CalCOFI | California Cooperative Oceanic Fisheries Investigations |
| CCS | California Current System |
| CICESE | Centro de Investigacio'n Cientifica y Educacio n Superior de Ensenada |
| COADS | Comprehensive Ocean Atmospheric Data Set |
| CODE | Coastal Ocean Dynamics Experiment |
| CoOP | Coastal Ocean Processes |
| CTD | Conductivity Temperature Depth |
| CTZ | Coastal Transition Zone |
| CZCS | Coastal Zone Color Scanner |
| EBC | Eastern Boundary Current |
| ENSO | El Niño/Southern Oscillation |
| EOS | Earth Observing System |
| ERS | European Remote Sensing |
| FAO | Food and Agriculture Organization |
| FORAGE | Fishery Oceanography Recruitment and Groundfish Ecology |
| Geosat | Geodesy Satellite |
| GFO | Geosat Follow-On |
| GLOBEC | Global Ocean Ecosystems Dynamics |
| GOES-NEXT | Geostationary Operational Environmental Satellite |
| IR | Infrared Radiation |
| JGOFS | Joint Global Ocean Flux Study |
| LIDAR | Light Detection and Ranging Instrument |
| MCC | Maximum Cross Correlation |
| MERIS | Medium-Resolution Imaging Spectrometer |
| MODIS | Moderate-Resolution Imaging Spectrometer |
| MODIS-N | MODIS nontilting version |
| MODIS-T | MODIS with tilting view angle |
| MPL | Marine Physical Laboratory |
| NCAR | National Center for Atmospheric Research |
| NMFS | National Marine Fisheries Service |
| NOAA | National Oceanic and Atmospheric Administration |
| NSCAT | NASA Scatterometer |
| NSF | National Science Foundation |
| ONR | Office of Naval Research |
| OPTOMA | Ocean Prediction Through Observation, Modeling and Analysis |
| OSLR | Ocean Science in Relation to Living Resources |
| PICES | Pacific Marine Science Organisation |
| RFP | Request for Proposals |
| ROV | Remotely Operated Vehicle |
| SAR | Synthetic Aperture Radar Search and Rescue |
| SARP | Sardine Anchovy Recruitment Project |
| SeaWiFS | Sea-Viewing Wide Field Sensor |
| SIO | Scripps Institution of Oceanography |
| SST | Sea-Surface Temperature |
| T-S | Temperature-Salinity |
| TOPEX | Ocean Topography Experiment |
| WOCE | World Ocean Circulation Experiment |

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