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NATIONAL OCEANIC AND ATMOSPHERIC ADMINISTRATION, NATIONAL MARINE FISHERIES SERVICE

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IN MEMORIAM

MICHAEL M. MULLIN
1937–2000

On 19 December 2000, Professor Michael M. Mullin died as a result of complications from heart bypass surgery. He was at home, recovering from the operation; he had planned a meeting at SIO on the next day. Without warning, the Marine Life Research Group lost its leader, CalCOFI lost a skilled and vigorous supporter, and we all lost a colleague, a shipmate, and a friend.

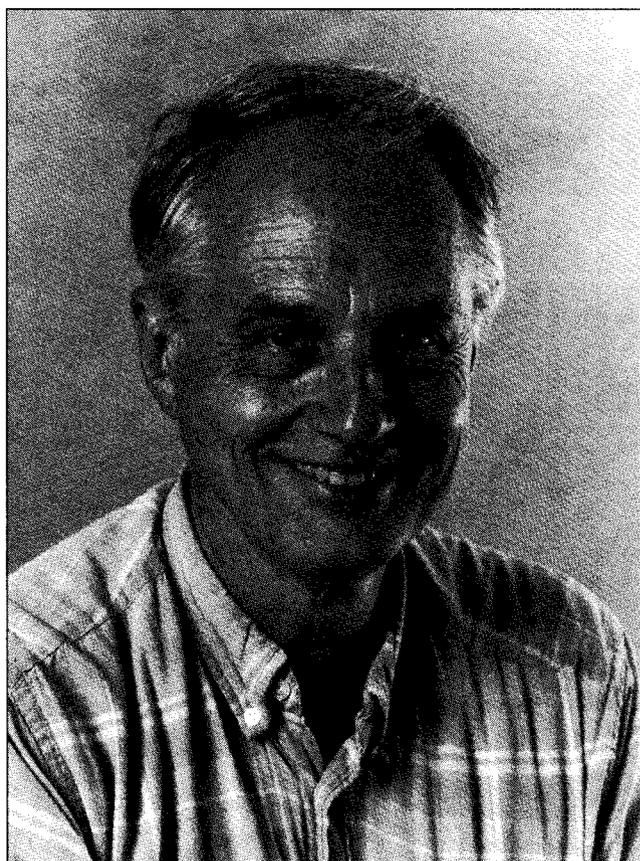
I first met Mike playing beach volleyball in 1964. Being tall and limber, he was a good man at the net, but never hogged the ball. Mike had recently earned his Ph.D. at Harvard/Woods Hole Oceanographic Institution and completed a year of postdoctoral work before accepting a position with the Food Chain Research Group at Scripps. He was planning to marry Connie, a Radcliffe College friend (much to the dismay of several of us single ladies). A year later, he joined the Scripps faculty.

In the following years, I sailed with Mike many times as he continued his research into the feeding ecology of planktonic copepods. He used some weird and wonderful sampling devices, including the bongo nets in their original stratified, opening-closing mode.

On a February 1973 expedition to the central Pacific I first realized Mike's love of Renaissance music. As we steamed into San Diego after a long journey, Mike and a small group stood on the bow singing "Never Weather-Beaten Sail" (Campian, 1612) to appropriately modified words: "...Seven knots, and seven knots and seven knots we sail. Neuston patches float in spots to fill our neuston pail..." They made the Channel 8 news.

Mike continually expanded his copepod research. Eventually, his study of how the environment affects copepods evolved to include the study of how the environment and copepods affect fish, leading him into fisheries oceanography. He published several research papers in that field, and a book with a typically terse and whimsical Mullin title: *Webs and Scales*. Mike's contributions to PICES were honored with a full biographical article published in *PICES Press* (January 2000, vol. 8, no.1*). In 1997, Mike became the editor of *Fisheries Oceanography*.

Because Mike was principled, rational, and fair, it was inevitable that he would be sought out for administrative positions. He served as director of the SIO Graduate



Department between 1977 and 1980, and as deputy director of SIO and dean of academic affairs between 1992 and 1996. In 1989, Mike was appointed director of MLRG, and as a consequence, became a member of the three-man CalCOFI Committee. Mike loved to teach and he loved his research, but I don't think he enjoyed administration. He seemed frustrated by the slow, tedious progress of "bureaucracy": the paperwork, the meetings, and the endless small conflicts. I suspect he accepted the administrative positions primarily out of a sense of duty. His frequent trips on CalCOFI cruises were an obvious escape into research.

Looking back, it is now clear that Mike made one extraordinary contribution as director of MLRG: he kept alive our participation in the CalCOFI program, and, almost certainly, the CalCOFI program itself. In view of the obstacles he encountered, this must have taken a near-Herculean effort.

*This article, written by David Checkley Jr., can be found at http://www.sio.ucsd.edu/scripps_news/pressreleases/mullin/mullin.pdf

When Mike assumed the directorship of MLRG, the CalCOFI program was suffering a serious image problem. If our academic colleagues thought about us at all, they thought of us as the “rich” program that endlessly repeated the same measurements, at the expense of (their) more innovative science. Because Mike’s directorship coincided with the start of CalCOFI’s fifth decade, he attacked the image problem head-on with a gala CalCOFI birthday party held at SIO. This was promotion on a grand scale. Prestigious speakers were invited from government and academic institutions outside the CalCOFI family to evaluate the program from their perspective. Their message was clear: the CalCOFI program of the past had pioneered the field of fisheries oceanography, and the CalCOFI of the present was poised to make major contributions to our understanding of global change. CalCOFI was not just important, it was essential. The symposium was impressive. A graceful ice sardine leapt from the center of a sumptuous lunch buffet. CalCOFI brochures and T-shirts were distributed, and a CalCOFI video was produced that is still shown on San Diego’s UCSD television channel.

Since then, the CalCOFI image has improved. Perhaps it was the fortieth birthday celebration; perhaps it was the scientific and societal interest in global change, or the aggressive recruitment of ancillary programs on the quarterly cruises, or the publication of several seminal papers that spawned headlines in the national and local press. Whatever the reason, Mike’s directorship saw a

marked increase in the recognition and appreciation of the CalCOFI program among our academic colleagues. As Mike wrote in 1999, the “...surveys of the California Current have metamorphosed from ‘mindless monitoring’ to the world’s premier time series of ocean physics and ecology (with no change in our basic work).”

However, Mike was faced with worse than image problems. In the early 1990s, the state of California suffered several years of budgetary shortfalls, and this was passed along to state agencies. Overnight, the MLRG portion of the CalCOFI budget was threatened with a cut of nearly 50%. At one point MLRG had secure funds for a single additional cruise, and we debated canceling cruises altogether and diverting existing funds toward analysis of data. It took budgetary magic and unending negotiations to keep CalCOFI going.

Mike would be the first to acknowledge that he alone was not responsible for these successes. Indeed, many of us stretched ourselves far outside previous boundaries to maintain and improve the CalCOFI program. Mike’s legacy to us was a continuing CalCOFI program. Our tribute to him must be a CalCOFI that moves vigorously into the challenges of the future.

I hope that some time before his death, maybe while bicycling to work wearing his orange signal-flag bike vest, Mike had a chance to look back over his directorship and to appreciate his accomplishments and to feel satisfied.

Elizabeth Venrick

Ode to the Standard Station

BY MICHAEL MULLIN
Expedition Dramamine II
22 April–20 May 1974

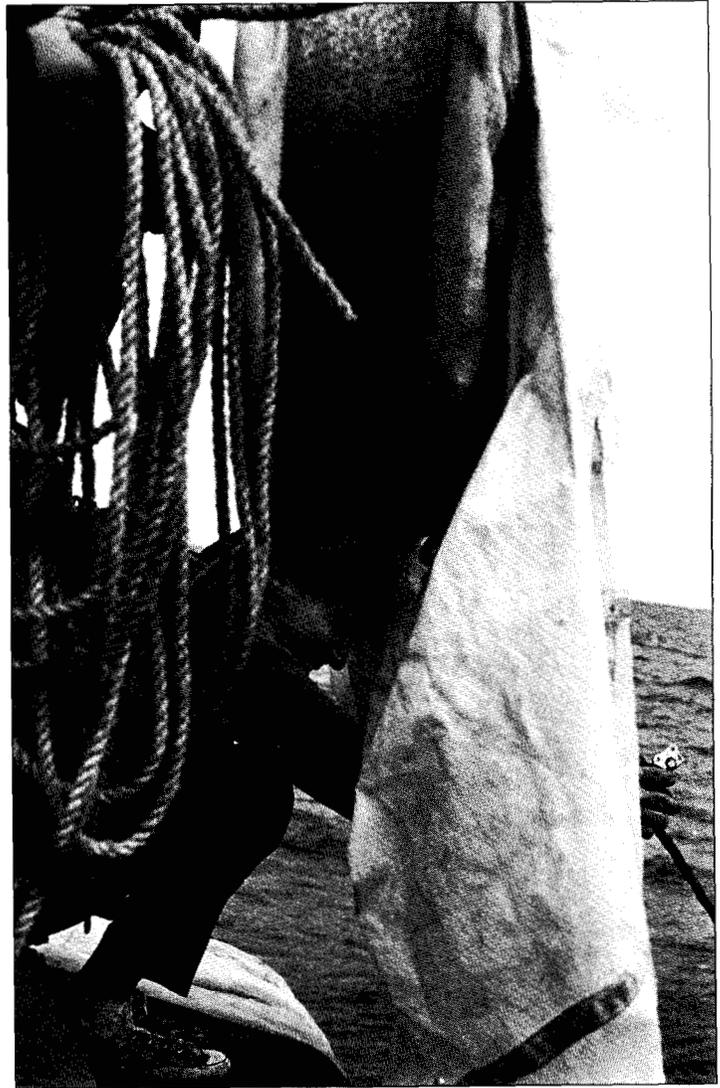
Oh, standard station, pride of science,
Boon to Oceanographer's self-reliance;
Mother Nature's forced compliance
borders upon rape

The sea which makes our feet get damp'll
Yield to us another sample,
Though 20's plenty and 50's ample
To make contours take shape.

The method hypothetico-deductive
For classroom use is quite instructive.
But Bill says it is too seductive,
Making mathematicians gape.

Each time we pose a brand new query,
Hoping to disprove a theory,
While our backs get sore and our eyes get bleary,
We log it on magnetic tape.

So we dock with reams of data.
Surely we will publish later,
For science is our Alma Mater
Salvation for the Upright Ape



Mike deploys a set of bongo nets.

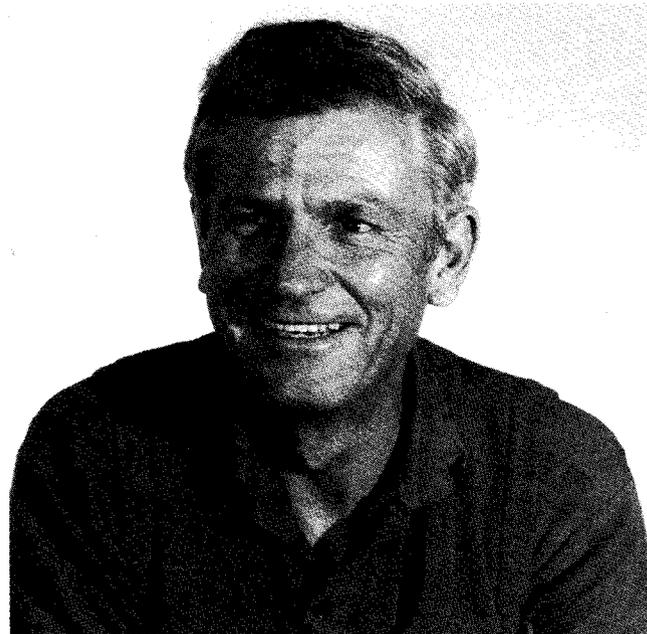
GARTH I. MURPHY
1923–2001

The founding CalCOFI coordinator, Professor Garth I. Murphy, died on 5 May 2001 in Woodland, California, at the age of 78. Before becoming coordinator in 1959, Garth was the director of the Pacific Oceanic Fisheries Investigations in Hawaii. After serving as coordinator until 1965, Garth was appointed professor of oceanography at the University of Hawaii. His principal contribution to CalCOFI and population dynamics was the thorough documentation of the fisheries on the sardine *Sardinops sagax* and interpretations of the causes for its decline along the west coast of North America. Two principal works followed this: a population projection of the recovery of the sardine, and the description of the function of multiple year-classes in the evolution of this and similar populations.

Murphy became interested in sardine at a three-day crisis meeting of 36 physical and biological oceanographers: the Rancho Santa Fe Symposium in June of 1958. In a question-and-answer session regarding how El Niño warming of the Pacific affected the sardine, Garth Murphy asked John Radovich, "What is the typical number of year-classes in a spawning [sardine] population?" Radovich said, "Predominantly three." Three decades before, the answer would have been "ten." This question marked the end of Murphy's 15-year career as biological technician and government administrator, and began his professional career as a graduate student in oceanography at Scripps Institution of Oceanography.

During his term as coordinator and as editor of *CalCOFI Reports* he transformed the publication from a gray literature of agency reports into an edited journal of original scientific contributions. Over the next five years he studied the Pacific sardine population and fishery with the help of mentors E. W. Fager, D. G. Chapman, M. Lloyd, and M. B. Schaefer.

During his tenure at the University of Hawaii, Murphy captured the practical significance of the longevity of sardine and founded a field of theoretical population biology concerned with the evolution of life history in variable environments. Theoretical ecologist Lamont Cole had found that a single reproductive period was essentially as useful to population maintenance as multiple reproductive periods. Murphy questioned Cole's view by using the history of the sardine population. He reasoned that sardines evolved repetitive reproduction and extended lifetimes after first maturity in response to



environmental variations. He believed that the joint influence of the fishery and the environment had affected the sardine by decreasing the number of reproducing year-classes from ten to three, thus making the sardine population sensitive to interannual, environmentally caused reproductive failure.

His rationale that preserving iteroparity, or multiple spawning, in a population protected it from collapse during short environmental events like El Niño aroused the wrath of the Peruvian government (which declared him *persona non grata*) when he blamed the collapse of the Peruvian anchoveta on overfishing by demographic truncation. He expressed these views during a United Nations Food and Agriculture mission study, to counter the accepted view that placed sole blame for the collapse of the anchoveta, the world's largest fishery, on the 1972 El Niño.

Garth Murphy's achievements in population biology have contributed to the CalCOFI time history; to the Pacific sardine, which recovered in the manner he predicted; to the practice of generalized population management under combined environmental and fishing pressure; and to theoretical population ecology.

Biological and fisheries oceanography has lost one of its earliest practitioners.

Paul E. Smith

Part I

REPORTS, REVIEW, AND PUBLICATIONS

REPORT OF THE CALCOFI COMMITTEE

A Year of Loss

The Marine Life Research Group (MLRG) and CalCOFI community received a major blow with the loss of MLRG Director Michael Mullin, who died on 19 December 2000, and Mia Tegner, Research Marine Biologist, who drowned in a diving accident on 7 January 2001. This issue of *CalCOFI Reports* is dedicated to Professor Mullin, who was a loyal and wise leader of the CalCOFI program for many years. Next year's issue of *CalCOFI Reports* will feature a symposium on abalone, one of Mia Tegner's specialties, and will be dedicated to her. This year we also lost the founding coordinator of CalCOFI, Professor Garth I. Murphy, who died on 5 May 2001.

CalCOFI Atlas 34

CalCOFI Atlas 34, entitled *Distributional Atlas of Fish Larvae and Eggs in the Southern California Bight Region: 1951–1998*, was published and distributed in March 2001. This atlas summarizes the distribution and abundance of 160 ichthyoplankton taxa collected in oblique plankton net tows on CalCOFI survey cruises from 1951 to 1998 in the Southern California Bight (SCB) region, the area encompassed by CalCOFI surveys since 1985. The atlas presents areal and temporal (seasonal, annual, and decadal) changes in occurrence and abundance of larval fish taxa in a format that permits the reader to interpret, in general terms, the effects that fisheries and ocean climate may have had during 1951–98. This is the third atlas summarizing CalCOFI ichthyoplankton data. CalCOFI Atlases 31 and 32 presented distributional summaries for all taxa taken on surveys that covered the greater CalCOFI sampling area extending from northern California to Cabo San Lucas, Mexico, during 1951–84.

Sardine Migration Model

The rapid recovery of Pacific sardine, now ranging from Baja California to Alaska, has caused us to reexamine working hypotheses, particularly those associated with population dynamics. While the mixing of the southern and northern sardine stocks may be too complete to support genetic separation, managing the species as one stock may be deleterious. The analyses of basic

population dynamics, as well as feeding and genetic studies, have been based on sardine taken largely within 20 miles of the coast. Most of the reappraisal stems from the preeminence of sardine spawning off the central California coast north of our current CalCOFI pattern, as measured by David Checkley's egg pump, as well as from adult sardine collected outside of the CalCOFI pattern by a cooperative Russian cruise.

Pacific sardine population parameters are being re-examined by Paul Smith and Nancy Lo in light of the finding that the principal portion of the population has not been available to the fishery. This has required revising the size and age composition of the "virgin" stock as related to two principal habitats. The southerly sardine population has an affinity for nearshore habitats and matures at a younger age and smaller size than the northerly population. Since body size is a principal feature of migration, the researchers have selected a migration model originally devised for hake to reproduce the major features of the recovering sardine population. This study is being geared to the revision of sardine management models to be introduced within two years.

Survivors' Habitat

CalCOFI oceanographic and ichthyoplankton data have been used to characterize larval fish survivors' habitat. Paul Smith, Elizabeth Logerwell, and Shannon Cass-Calay have continued this work by investigating the causes for large variations in the sizes of pelagic fish populations in and around the California Current complex. Distribution of early life stages can provide practical information on the size of the adult spawning stock with enough precision for the fishery-independent component of stock assessment. The size of the adult stock and the production and survival of the spawn they produce is independent of the recruitment from that year's reproductive effort. Anchovy and hake growth rate studies by John Butler and associates have shown that growth of larval and juvenile stages is quite variable and that faster-growing individuals are better represented as survivors. Logerwell and Smith have concentrated on horizontal mesoscale features (anticyclonic eddies) on the high seas; these features appear to retain larvae and enhance growth and survival. Cass-Calay has concentrated

on small-scale layers of food aggregations, which are associated with the faster growth rates of deeper-living hake larvae.

Coastal Pelagic Species Management

The California Department of Fish and Game (CDFG) and the National Marine Fisheries Service (NMFS) are extensively involved in assessing and managing the coastal pelagic species fishery through the Pacific Fisheries Management Council (PFMC). Quarterly CalCOFI ichthyoplankton samples continue to play an important role in the annual assessment of Pacific sardine and Pacific mackerel; the PFMC uses these assessments to recommend harvest guidelines for the West Coast fishery. Additional northern stations, crucial for sardine assessments, were sampled during RV *Jordan* cruise 0104. Sardine egg data collected during the April cruise are used to estimate spawning biomass and spawning area. The latest sardine and mackerel biomass estimates and resulting harvest guidelines are summarized in the Review of Some California Fisheries section of this volume.

El Niño/La Niña

The 1997–98 El Niño was the strongest ever observed both in the equatorial zone and off California. Ron Lynn and Steven Bograd have completed a manuscript describing the strong variations in transport and water-mass characteristics during the 1997–99 El Niño/La Niña along CalCOFI station line 90. During El Niño, sea-surface temperature and sea level were anomalously high, the coastal zone thermocline was deep, and the inshore countercurrent attained record values of poleward transport. The change to La Niña conditions in early 1998 was abrupt and dramatic, as water temperatures dropped below normal and the California Current greatly strengthened at the expense of the countercurrent. Bograd and Lynn have also described the strong variations in the nutricline and the resulting response of primary and secondary production during the same period along CalCOFI lines 80 and 90. The initial period displayed a depressed nutricline and low productivity and was followed by an abrupt and strong reversal as La Niña became established.

Juvenile Rockfish Survey

The regular CalCOFI ichthyoplankton survey provides information on seasonal production of larvae but little information on spatial patterns of survival later in the pelagic phase. During the summer of 2000, a micro-nekton survey of the Southern California Bight was conducted with a 10 m² multiple opening/closing net and environmental sensing system (MOCNESS). The primary goals of the cruise were to investigate the depth and spatial distributions of target species and to deter-

mine the feasibility of using data on late larvae/pelagic juvenile abundance of rockfishes as a fishery-independent indicator of recruitment and year-class strength. Secondary objectives were to examine similar questions for squid, sardine, and anchovy. Many rockfish larvae cannot be visually identified to species, so molecular genetic techniques are being used to identify the larvae. This approach has given new insights into the depth preferences and survivors' habitat for individual rockfish species. Preliminary results suggest that the MOCNESS is an effective means of sampling the abundance of prerecruit stages of rockfishes. Another cruise is planned for 2001.

SIO Research Highlights

Recent MLRG research highlights include the awarding of a U.S. GLOBEC grant to Mark Ohman and collaborators to continue their retrospective analysis of CalCOFI macrozooplankton samples. The objectives are to understand shifts in zooplankton species assemblages in relation to interdecadal changes in physical properties of the upper ocean and atmosphere. In collaborative work with Ed Brinton, they are also solving for stage-specific mortality rates for the dominant euphausiid species in the California Current system (CCS), to provide regime-specific mortality rates appropriate for ecosystem models.

SIO graduate student Ginger Rebstock completed her dissertation, "Long-Term Changes in the Species Composition of Calanoid Copepods off Southern California." She enumerated copepods from CalCOFI zooplankton samples that were collected from 1951 through 1999, and analyzed low-frequency population fluctuations in the context of interannual to interdecadal climate variability. The study showed species-specific responses to environmental variability, and strong responses to decadal-scale climatic regime shifts in some, but not all, species. She found that in spite of these individual responses and large environmental changes in the CCS, the dominance structure of the calanoid copepods has remained stable over 49 years.

Scripps Institution of Oceanography is reorganizing to reduce its number of research divisions. The MLRG is merging with the Center for Coastal Studies. It is expected that this combined unit will continue to actively participate in the CalCOFI program.

California Marine Legislation

The Marine Region of the CDFG continues to be active in the management of nearshore marine resources in California. In the year 2000, the Marine Life Management Act (MLMA; AB 1241) is the blueprint for how marine resources will be managed in California. Marine Region staff began to implement these new policies, which include science-based management, adap-

tive management, an ecosystem approach, and constituent involvement.

A master team whose task will be to establish a network of marine protected areas (MPAs) in California was established in 2000, as mandated in the Marine Life Protection Act (AB 993). The team has simplified the classification system for MPAs into three categories: reserves, parks, and conservation areas. The team will now begin to select MPAs, with input from all interested groups and the public. CDFG's Marine Region has developed a geographic information system (GIS) laboratory to support this effort.

Abalone Management

The CDFG's Nearshore Invertebrate Program continues its work toward managing and conserving invertebrate resources. The Abalone Recovery and Fishery Management Plan is due to be presented to the state legislature on 1 January 2003. CDFG biologists examined red abalone and red sea urchin populations inside and outside marine protected areas in northern California to determine how fishing affects these resources. The department continued to monitor depleted abalone populations in southern California. This work included joint surveys with the NMFS to investigate white abalone habitats.

Kudos

The seagoing personnel of SIO's MLRG, the Southwest Fisheries Science Center's Fisheries Resources Division, and CDFG's Marine Region all contributed, through dedication and diligence, to the success of CalCOFI's quarterly fieldwork. The Committee thanks the officers and crews of the research vessels that have served us well as platforms for our observations during the past year: the NOAA ship *David Starr Jordan*, the University of California RVs *New Horizon*, *Roger Revelle*, and *Robert Gordon Sproul*, and the CDFG RV *Mako*.

We also thank the reviewers of contributed papers in volume 42: Larry Allen, Richard Beamish, Darrin Bergen, John Butler, Greg Cailliet, Phil Hastings, Annette Henry, John Hunter, Elizabeth Logerwell, Milton Love, Bev Macewicz, Mike Maxwell, Alan Mearns, Geoff Moser, Richard Parrish, Antonella Preti, Frank Schwing, Paul Smith, and Russ Vetter. We are especially grateful to Julie Olfe for editing another fine volume in this long series of publications.

The CalCOFI Committee:

Kevin Hill, CalCOFI Coordinator

John Hunter, NMFS

Laura Rogers-Bennett, CDFG

Elizabeth Venrick, UCSD

REVIEW OF SOME CALIFORNIA FISHERIES FOR 2000: MARKET SQUID, SEA URCHIN, PRAWN, WHITE ABALONE, GROUND FISH, OCEAN SALMON, PACIFIC SARDINE, PACIFIC HERRING, PACIFIC MACKEREL, NEARSHORE LIVE-FISH, HALIBUT, YELLOWFIN TUNA, WHITE SEABASS, AND KELP

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SUMMARY

In the year 2000, commercial fisheries landed an estimated 247,122 metric tons (t) of fishes and invertebrates from California ocean waters (fig. 1), an increase of 15% from the 214,229 t landed in 1999. The preliminary ex-vessel economic value of California commercial landings in 2000 was \$133 million, a decrease of 8% from \$145 million in 1999.

Kelp harvesting was worth an estimated \$40 million in 2000 to the major harvester and producer of algin in California, ISP Alginates Inc. This exceeds ex-vessel values for market squid, the top-producing fishery in the state. As they did in 1999, in 2000 the commercial invertebrate fisheries in California had a greater combined ex-vessel value (\$68 million) than the combined values for finfish fisheries (\$65 million). The top three fisheries for 2000 (excluding kelp) in gross ex-vessel value were market squid (\$27 million), groundfish (\$20 million), and Dungeness crab (\$14 million). Market squid landings increased again, with a new record high. Sea urchin landings, worth \$13 million in 2000, continued their downward trend since the historic high in 1988. Ridge-back prawn increased 20%, while spot prawn decreased 28%. Dungeness crab landings decreased 35% compared with 1999, when landings were near the 10-year average. The recreational red abalone fishery in northern California landed an estimated 703,000 abalone, or 1,196 t, which was close to the 4-year average (1986–89).

Ocean conditions along the California coast recovered from the wild temperature fluctuations following the 1997–98 El Niño event and the 1999 La Niña. Pacific sardine landings remained high, while Pacific mackerel landings rebounded from their 1999 low to 1997–98 levels. Pacific herring continued to recover from the devastating effects of El Niño with a 16% increase in landings during the 1999–2000 sac roe season. Commercial chinook salmon landings in the ocean continued to increase, but remained at almost half of the 1988 high. Commercial white seabass landings declined slightly from their 18-year high in 1999.

Swordfish landings increased again, by more than 39%. Thresher shark landings continued to decline (by 2 t),

although shortfin mako increased from 42 to 55 t (31%). In October 2000, the shark finning prohibition act (HR 5461) was passed; it bans shark finning inside the United States Exclusive Economic Zone.

Landings in the commercial groundfish fishery in 2000 remained at half of the 1990 value, but increased slightly compared with 1999. The groundfish harvest was again dominated by Dover sole, thornyheads, sablefish, rockfish, and Pacific whiting. As a result of new stock assessments, several groundfish species were declared overfished; they include lingcod, bocaccio, Pacific ocean perch, and some rockfish. The Pacific Fishery Management Council (PFMC) established a separate optimal yield for cowcod and drastically reduced both commercial and recreational levels of take; the council is also considering plans to establish a cowcod closure area. Rebuilding plans for cowcod and canary rockfish were developed in 2000 for implementation in 2001. Draft rebuilding plans have called for greatly reduced landings not only for the overfished species, but also for species associated with them.

The live-fish fishery in California continued its exponential growth. Although there was a slight decrease in landings, increased prices resulted in a higher ex-vessel value for the fishery than in 1999. The total ex-vessel value of the live-fish fishery was approximately 12% of the value of the groundfish fishery as a whole.

Statewide landings by recreational fishers aboard commercial passenger fishing vessels (CPFVs) decreased by 14%, to 2,923,535 individual fishes, despite an increase (3%) in the number of anglers. Southern California CPFV landings constituted 83% of the statewide total. Recreational landings of ocean salmon increased to 179,700 chinook salmon, more than double the landings in 1999, while the coho salmon fishery remained closed. Recreational landings of white seabass continued to increase in 2000, to 16,082 fish—nearly a 10-fold increase since 1982.

The Marine Life Management Act (MLMA) requirements for fishery management plans (FMPs) dominated much of the work in the California Department of Fish and Game (CDFG) as biologists worked to draft

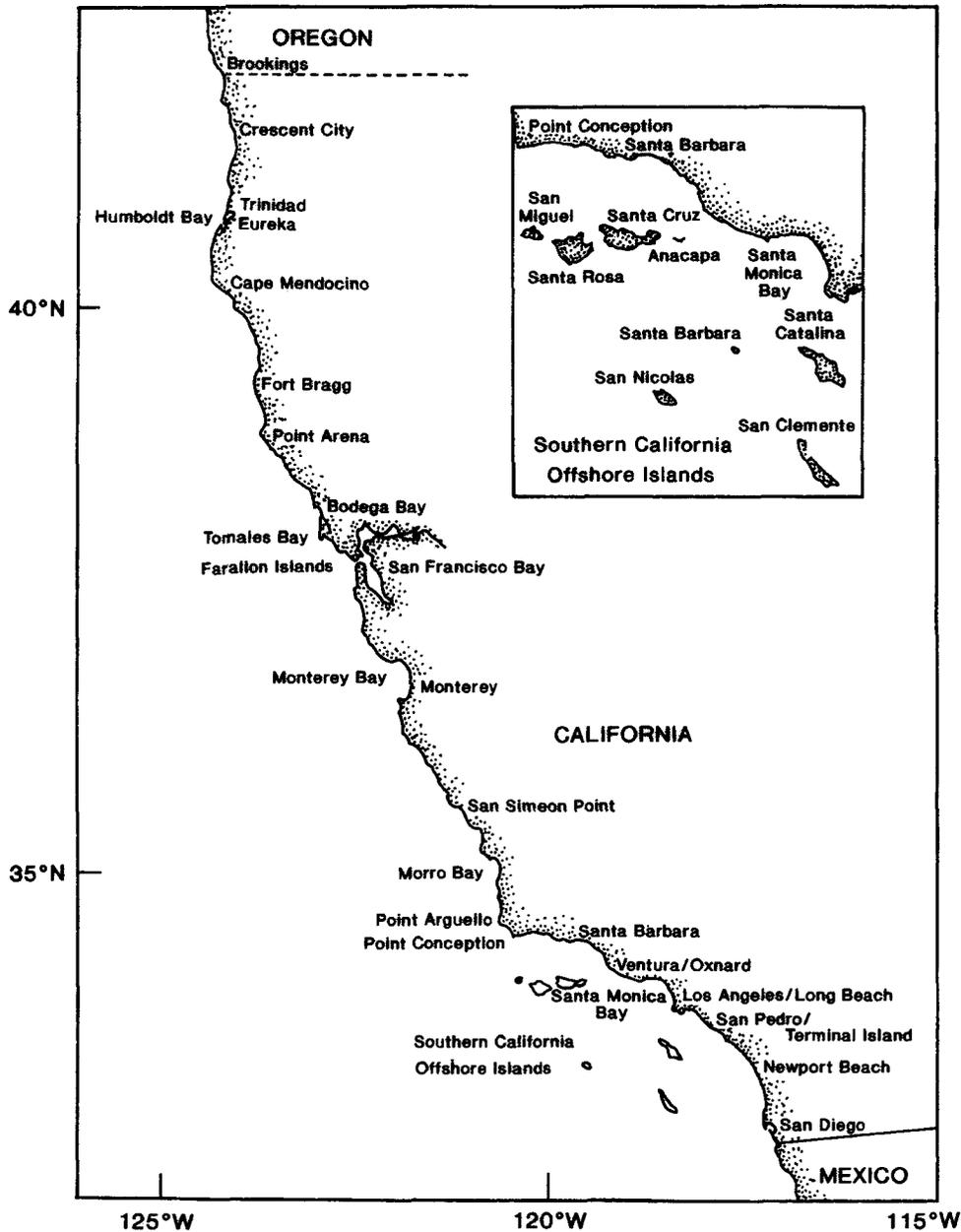


Figure 1. Map of California ports and fishing areas.

FMPs for nearshore fishes, white seabass, and abalone. As part of this effort, the CDFG addressed many of the plans' requirements for constituent involvement. The Marine Life Protection Act moved forward with the establishment of a scientific panel to select marine protected areas in California. As part of the nearshore fishery management plan, the CDFG is considering an ecosystem-based approach to implementing a network of sites to be monitored for nearshore rocky subtidal species such as rockfish, abalone, and red sea urchin. This network would encompass sites inside marine protected areas as well as fished sites both close to and far from ports. Subtidal work continued in 2000 to map areas for assessments

and to help determine stock abundances. The Geographic Information Systems Laboratory constructed maps for the nearshore finfish species, showing spatial patterns in the distribution of landings. Biologists completed kelp bed assessments: fly-over data from 1999 (46 sq. kilometers) and 1989 (103 sq. kilometers) show a 56% decrease in kelp surface area in the state over the decade.

INVERTEBRATE FISHERIES

Market Squid

Market squid is one of the most important fisheries in the state, in terms of both volume and revenue. In

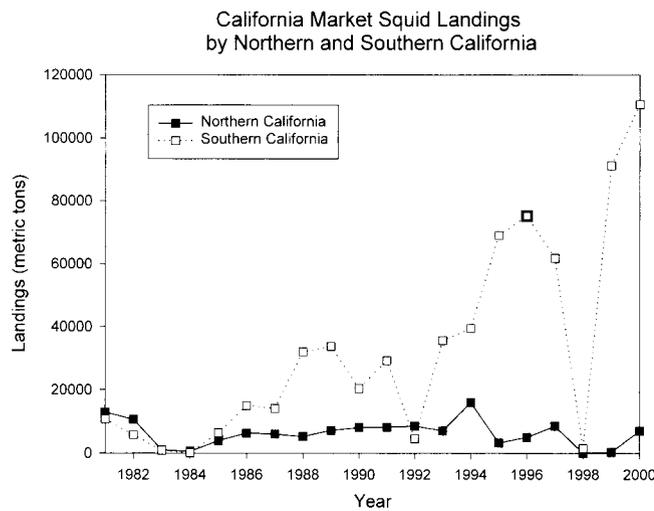


Figure 2. Northern and southern California market squid landings, 1981–2000.

2000, 117,890 t were landed, with an ex-vessel value of approximately \$26 million. These landings set a new record, surpassing the previous high of 90,322 t set in 1999. While landings were high, the average price paid to fishers was \$220 per t, a 43% drop from 1999. The fishery remained strong after the 1998 El Niño, which decreased landings to less than 2,000 t in 1998.

Market squid was a major fishery export product, with 51% of the catch sold to buyers outside the United States. The total export value was \$48,196,174, with China the top export destination (22,940 t). Domestically, the product was sold throughout the United States to restaurants, Asian markets, and (frozen) as bait.

The California market squid fishery is unique in that two vessels are usually involved in fishing: a light vessel, which uses intense lighting to attract the squid to the surface, and a seine vessel, which surrounds the school with a net to capture the squid. The fishery targets large aggregations of spawning squid over a sandy substrate.

There are two centers for this fishery: the Monterey Bay region of central California and the Channel Islands in southern California. Prior to the early 1980s, the northern fishery contributed the larger portion of the statewide catch. The southern fishery grew as demand for the species increased, and it is now the dominant area of the fishery (fig. 2). The northern fishery season is typically spring through fall. The southern fishery season takes place during the fall and winter. In 2000, the Monterey fishery recovered from the effects of El Niño with 6,995 t (6% of catch) landed; only 297 t were landed in 1998 and 1999 combined. The southern fishery landed 110,894 t (94% of catch) in 2000. As in the past, catch levels were regulated by market demand for most of the year.

New regulations on squid-attracting lights were adopted by the Fish and Game Commission, and implemented by the CDFG in spring 2000. These regulations require all squid fishing vessels to limit their squid lights to 30,000 watts, shield the entire filament of each light, and orient the illumination downward or keep the lights underwater. These regulations were enacted to avoid interactions with nocturnal seabirds and to reduce light scatter in coastal communities.

In 1999, the Fish and Game Commission adopted two regulations based on recommendations from the Squid Fishery Advisory Committee and the CDFG, which implemented them in early 2000. One regulation involves closing the squid fishery from noon on Friday to noon on Sunday, statewide, to allow squid time to spawn uninterrupted. The other requires operators of vessels fishing for squid to complete a daily logbook. Information from logbooks will be used to determine fishing effort and location.

In recent years considerable information has been obtained about the status of market squid populations and the fishery. Department-funded research by biologists at the National Marine Fisheries Service has produced preliminary results on fecundity and spawning escapement that have management application. To determine fecundity, researchers used microscopic analysis of the ovary to estimate that each female lays approximately 4,600 eggs before completing her life cycle. A mantle-condition index was developed to measure tissue loss in relation to spawning activity. Research shows a relationship between the mantle-condition index and the number of eggs spawned. The mantle index was lower in squid that released more eggs. With this information, a mathematical model can be used to estimate the amount of spawning escapement.

Sea Urchin

Red sea urchin (*Strongylocentrotus franciscanus*) fishery landings statewide were off by 383 t, to 6,046 t (13.3 million pounds) in 2000 compared with 6,429 t in 1999. This continues the steep decline in landings since the record high in 1988, when landings were 23,981 t. Ex-vessel value held steady at about \$13.1 million as prices improved and some dealers reported increasing the proportion of their product sold to U.S. markets.

The northern California catch has been under 2,269 t (5 million pounds) since 1995, after peaking at over 13,600 t (30 million pounds) in 1988 (fig. 3). Effort, as vessel trips, has ranged from 2,300 to 4,200 during this period. Commercial sea urchin divers can move freely from region to region, and in 1999, 18% of all divers (with >10 landings) fished exclusively in northern California. A total of 99 divers (24%) of the 421 permitted divers statewide in 1999 caught more than 50%

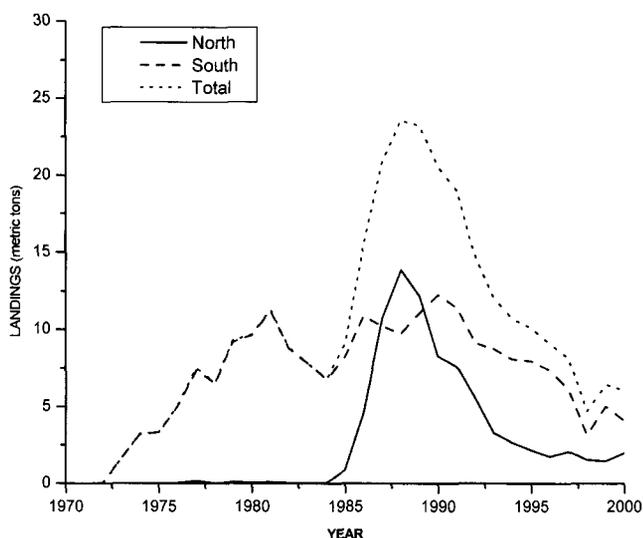


Figure 3. Northern and southern California landings of red sea urchin, 1971–2000.

of their catch in northern California, which produced 23% of the statewide catch. Latent effort is high in this fishery: 17% of the permittees took 50% of the statewide catch, and 90% of the catch was taken by 264 divers (63%). Overcapitalization in this industry may have been exacerbated by the closure of the commercial abalone fishery in 1997. Many of the participants, gear, and boat requirements are the same for both of these fisheries.

Subtidal surveys at northern California index sites in 1999 and 2000 indicate depressed abundances and recruitment levels for red sea urchin in fished sites compared with protected sites.

Southern California's red urchin catch fell below 4,535 t (10 million pounds) in 2000, for the second time in the last 25 years (fig. 3). Of the three regions comprising this area—the northern Channel Islands, the southern Channel Islands, and the mainland coast—the northern islands have contributed most of the catch over the years. But the catch from these islands has fallen from nearly 7,256 t (16 million pounds) in 1991 to just over 1,361 t (3 million pounds) of red urchins in 2000. The principal islands of the northern group are San Miguel, Santa Rosa, and Santa Cruz; the former two have provided most of the catch during the last decade. Availability estimates for kelp beds at these two islands (from ISP Alginates Inc.) are highly correlated with red urchin harvests during the period 1989–97.

No significant sea urchin management measures have been enacted since 1992, and the fishery has continued on a downward trend as industry and managers have been at an impasse over the best course of action. One important management measure recommended by the CDFG's Nearshore Invertebrate Team is the imposition of a maximum size limit in addition to the present min-

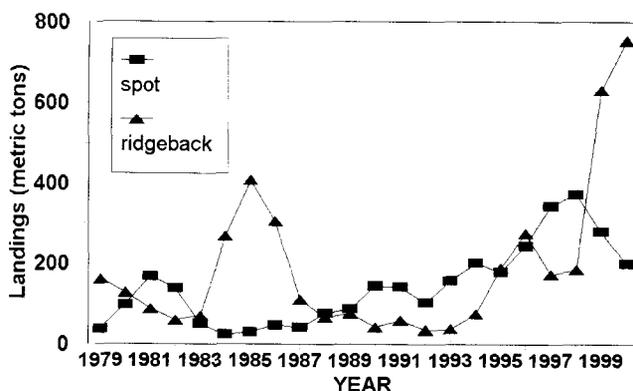


Figure 4. California ridgeback and spot prawn landings, 1979–2000.

imum size limit. Extensive field work and modeling of sea urchin population dynamics indicate that such a limit would protect urchins with the greatest spawning potential and enhance the survival of juvenile urchins under the spine canopy of larger urchins. The team suggested a maximum size limit of 12.1 cm (4.75 inches) in the north and 11.4 cm (4.5 inches) in the south. In 2000, about 12% of the northern catch exceeded the proposed limit, while in the south less than 1% was larger than 11.4 cm. Although urchins exceeding the upper size limits have become scarcer, growth studies suggest that once red urchins escape the fishery they could live and reproduce for decades.

Spot and Ridgeback Prawn

Spot prawn. Preliminary 2000 spot prawn (*Pandalus platyceros*) landings were 199 t, a 28% decrease from the 278 t landed in 1999. This was the second consecutive year of decreasing spot prawn landings (fig. 4). The largest decline occurred in the Santa Barbara area trawl catch, where spot prawn landings dropped 40 t from the previous year's total of 150 t.

Spot prawn are caught with both trap and trawl gear. A total of 75 vessels (39 trap and 36 trawl) made landings in 2000. Table 1 shows types of gear and landings for spot prawn by port area. Some trap and trawl vessels fished in several different port areas during the year. Over half of the combined trap and trawl spot prawn landings in 2000 were made in the Santa Barbara port area. In the past, boats using trap gear were the major contributors to the fishery. Since the mid-1970s, however, boats using trawl gear have increased in number, and their landings now dominate the fishery. In the last ten years the number of spot prawn trawlers has increased even more rapidly with an influx of vessels from other groundfish fisheries that have been subjected to increasingly restrictive quotas or season closures.

Trawlers harvested approximately 121 t of spot prawn in 2000, while trappers took 78 t (table 1). The median

TABLE 1
 California 2000 Spot Prawn Landings by Port Area and Gear Type

Port areas	Number of fishing vessels by gear type		Spot prawn landings (metric tons)			Percentage of total
	Trap	Trawl	Trap	Trawl	Totals	
Eureka	0	2	0	9	9	5
San Francisco	1	4	<1	22	22	11
Monterey	11	6	13	5	18	9
Santa Barbara	12	27	30	80	110	55
Los Angeles	10	3	18	5	23	12
San Diego	10	0	17	0	17	8
Totals			78	121	199	100

ex-vessel price paid for all spot prawns was \$9.00 per pound. Approximately 82% of all spot prawn were sold live. Live spot prawn had a median ex-vessel price of \$9.00 per pound, with a range from \$2.00 to \$11.00 per pound. Fresh dead spot prawn sold for a median ex-vessel price of \$3.50 per pound, with a range from \$2.00 to \$4.00 per pound.

During 2000, the trap and trawl spot prawn permit fisheries in southern California (south of Point Arguello) operated under concurrent closures running between 1 November and 31 January. Up to 50 pounds of incidentally trawled spot prawns could be retained during the closure. This southern California trap and trawl closure was enacted in 1997 to provide more protection for gravid females. North of Point Arguello the spot prawn season was open all year.

Concern over bycatch in the fishery led the CDFG and the Fish and Game Commission to mandate an on-board spot prawn observer program in 2000. Trawl and trap fishermen landing spot prawns were required to purchase an observer stamp; the stamp funds were used to hire, train, and deploy observers on spot prawn vessels. Beginning in August 2000, CDFG onboard observers were sent out on spot prawn trawl and trap vessels to monitor bycatch. Observers completed 12 single-day trips on trap vessels and 13 days on trawl vessels, documenting the bycatch in 104 trap strings and 37 trawl tows. The collection and analysis of observer data is scheduled to continue through the 2000–2001 season.

Ridgeback prawn. Preliminary 2000 ridgeback prawn (*Sicyonia ingentis*) landings totaled 755 t. This represented a 20% increase in landings from the 632 t landed in 1999 (fig. 4) and was the highest total recorded since the fishery began in the late 1970s. Ridgeback prawn landings in both 1999 and 2000 were more than double the annual landings recorded in each of the previous four years. The availability of ridgeback prawn on the trawl grounds, coupled with a growing market demand for both dead and live ridgeback prawns, accounted for the greatly increased level of landings. Most of the ridgeback prawn

were frozen whole and delivered to both domestic and overseas markets.

Ridgeback prawn are taken exclusively by trawl nets, and there is a closed season from 31 May through 1 October, when an incidental catch of 50 pounds is allowed. Forty-eight trawl vessels made ridgeback prawn landings in 2000, an increase of 13 from the number of vessels that fished in 1999. All of the landings were made at southern California ports, between Santa Barbara and Los Angeles, and almost all ridgeback prawn were caught within the Santa Barbara Channel.

The median ex-vessel price for ridgeback prawn was \$1.25 per pound. Approximately 36% of the landings were live, an increase over the 28% live ridgeback prawn landed in 1999. Live ridgeback prawn sold for a median ex-vessel price of \$1.40 per pound; the median ex-vessel price for dead ridgeback prawn was \$1.00 per pound.

Until 1998 ridgeback prawn landings were limited by market demand and the number of dealers who could buy and process large quantities of prawns. In 1999 and 2000 market conditions changed, and there were at least five dealers who purchased 100,000 to 300,000 lbs. of ridgeback prawn annually. This was in addition to the more than 40 other dealers who purchased lesser quantities. Although there are currently no biomass estimates or maximum sustainable yield (MSY) calculations for ridgeback prawn, the recent substantial increases in landings warrant further monitoring and analysis of the fishery to determine if the current harvest levels are sustainable.

White Abalone

In 1997 the National Marine Fisheries Service (NMFS) designated white abalone (*Haliotis sorenseni*) as a candidate species for listing under the Endangered Species Act. The following year, NMFS contracted with Scripps Institution of Oceanography to review the biological status of white abalone. The comprehensive status review of the white abalone was completed in early 2000. The NMFS concluded that the white abalone was in danger of extinction throughout a large portion of its

range, and issued a proposed ruling to list white abalone as an endangered species. A consortium of public and private agencies, including the CDFG, NMFS, National Park Service, University of California (Scripps Institution of Oceanography and UC Santa Barbara), U.S. Geological Service, Channel Islands Marine Research Institute (CIMRI), and Marine Conservation Biology Institute are working on the recovery of white abalone.

Several cruises, supported by a Saltonstall-Kennedy grant and the NMFS Southwest Fisheries Science Center, were made in 2000 to begin collecting broodstock for culture, research, and species restoration. The collection cruises focused on historical white abalone habitat around Santa Catalina Island. One of the cruises used a remotely operated vehicle (ROV) owned and run by NMFS to search for white abalone habitat. The ROV proved effective for finding white abalone and thus helping to conserve scuba time for collecting animals at deep depths. Fourteen abalone were collected and are now in captivity in two culture facilities, UC Santa Barbara and CIMRI.

FINFISH FISHERIES

Groundfish

The California commercial groundfish harvest for 2000 was 16,386 t (table 2). Total landings increased 15%, or 2,180 t, from 1999. Compared to 1990, however, landings have decreased 51%, or 14,726 t. The year 2000 increase in landings is due to increases in Pacific whiting (*Merluccius productus*): when Pacific whiting data are removed, both the 1999 and 2000 total harvests of remaining groundfish decrease, and the 2000 harvest is down 12% from 1999. The ex-vessel value for all groundfish in 2000 was approximately \$20.2 million, an increase of \$1.4 million, or 8%, from 1999 revenues.

In 2000, 89% of the groundfish landed were taken by bottom and midwater trawl gear, a slight increase from 86% in 1999. Line gear accounted for the second largest amount at 9%, a slight decrease from the 12% observed in 1999. The line gear contribution was at a recent high of 18% in 1992. The gill and trammel net component remained at just under 1% after a steady decline from 5% in 1993 to 1% in 1996. Traps again accounted for a little over 1% of total groundfish landings.

California's groundfish harvest was again dominated by Dover sole (*Microstomus pacificus*), thornyheads (*Sebastes* spp.), sablefish (*Anoplopoma fimbria*), rockfish (*Sebastes* spp.), and Pacific whiting. Landings of Dover sole, thornyheads, and sablefish (the DTS complex) showed a moderate drop, while lingcod and all rockfish except widow rockfish showed sharp declines in 2000. The declines in lingcod and rockfish, other than widow rockfish, reflect highly restrictive landing limitations adopted by the

TABLE 2
 California Commercial Groundfish Landings (Metric Tons)

	1999	2000	Percent change
Flatfish			
Dover sole	3,745	3,267	-13
English sole	375	299	-20
Petrale sole	529	628	19
Rex sole	282	223	-21
Sanddabs	925	727	-21
Other flatfish	141	115	-18
Rockfish			
Thornyheads	1,467	1,240	-16
Widow rockfish	574	705	23
Chilipepper	885	444	-50
Bocaccio	70	27	-61
Splitnose rockfish	138	78	-44
Other rockfish	1,152	744	-35
Roundfish			
Lingcod	153	54	-65
Sablefish	1,905	1,859	-2
Pacific whiting	1,308	4,986	281
Grenadier	312	221	-29
Cabezon	144	112	-22
Other groundfish	101	633	527
Total	14,206	16,386	15

PFMC in November 1999 to reduce the harvest of depleted stocks. Shoreside landings of Pacific whiting returned to recent levels after dropping in 1999 because of reduced availability in the Eureka-Crescent City area during spring and early summer. The 1999 decline was not related to the health of the whiting stock, but most likely was caused by a disruption in their normal migratory pattern related to the 1999 La Niña.

For 2000 the PFMC continued to set optimal yields (OYs) for Dover sole, shortspine thornyhead (*Sebastes alascanus*), longspine thornyhead (*Sebastes altivelis*), sablefish, Pacific whiting, lingcod (*Ophiodon elongatus*), bocaccio (*Sebastes paucispinis*), canary rockfish (*Sebastes pinniger*), chilipepper (*Sebastes goodei*), Pacific ocean perch (*Sebastes alutus*), splitnose rockfish (*Sebastes diploproa*), widow rockfish (*Sebastes entomelas*), and yellowtail rockfish (*Sebastes flavidus*). Also, as a result of a new stock assessment, the PFMC established a separate OY for cowcod (*Sebastes levis*) in the Monterey and Point Conception INPFC areas.

In early 1999 the NMFS notified the PFMC that lingcod, bocaccio, and Pacific ocean perch were overfished. In response the PFMC was required to prepare rebuilding plans with the goal of rebuilding stocks within 10 years, if possible. The rebuilding harvest levels contained within the rebuilding plans required the PFMC to set 2000 OYs for lingcod and bocaccio at half of what they were in 1999. In addition, canary rockfish and cowcod assessments completed in 1999 indicated that those species were also overfished and required rebuilding plans to be

developed during 2000 for implementation in 2001. In anticipation of the need for a greatly reduced canary rockfish harvest in 2001, the 2000 OY for that species was also reduced. The PFMC again used cumulative landing limits as well as trip limits to meet their objective of staying within the annual OYs for all groundfish while continuing to provide for a year-round fishery.

In order to constrain landings of the overfished rockfish species and lingcod to the yields recommended in the draft rebuilding plans, it was necessary to also limit the take of species normally associated with them. While the fully assessed rockfish species were managed with discrete OYs, the rockfish that had not been fully assessed had been aggregated into a single management category—"the *Sebastes* complex"—with a single OY. The PFMC, faced with drastic rockfish harvest reductions, recognized that the overfished species are shelf species associated with other shelf species, and thus it was not necessary to reduce the harvest of all rockfish. So, for this and other reasons, the PFMC separated the unassessed rockfish into three management assemblages, each with their own OY. The assemblages—minor nearshore, minor shelf, and minor slope—can now be managed with their own OYs and trip limits affording protection for depleted stocks while still providing fishing opportunities for more abundant stocks.

For 2000 the PFMC adopted highly restrictive landing limits for lingcod and the shelf rockfish group. These limits were designed to constrain total catch of lingcod, bocaccio, and canary rockfish to the small optimum yields necessary to rebuild their stocks. An exception was made for widow rockfish and chilipepper, which could be taken in larger amounts if a vessel had only midwater trawl gear onboard. The use of this option is reflected in the relatively higher widow rockfish landings (table 2); however, fishers were unable to catch chilipepper rockfish in any quantity with midwater trawl gear. In order to further discourage targeting on shelf rockfish, the PFMC also adopted an idea proposed by industry that prohibits the landing of anything other than the DTS complex or slope rockfish when large footrope trawl gear (footrope greater than 8 inches) is onboard a vessel. Vessels fishing for shelf flatfish must use a net with a footrope smaller than 8 inches.

During the year 2000, stock assessment teams reported on coastwide lingcod, bank rockfish (*Sebastes rufus*), darkblotched rockfish (*Sebastes crameri*), widow rockfish, and yellowtail rockfish. These assessments were reviewed by stock assessment review (STAR) panels, whose recommendations were forwarded to the Groundfish Management Team (GMT) for development of 2001 management measures. The GMT addressed the STAR panel recommendations as well as the NMFS notice that widow rockfish and darkblotched rockfish were overfished and

that in 2001 the PFMC needed to develop rebuilding plans for implementation in the 2002 management cycle.

Also in 2001 the PFMC will continue to investigate a groundfish industry capacity-reduction program, and implement a groundfish observer program. Stock assessments planned for 2001 include black rockfish (*Sebastes melanops*), Dover sole, shortspine thornyhead, sablefish, and Pacific whiting. Another goal is the implementation of a permit-stacking option in the limited-entry fixed-gear sablefish fishery.

Ocean Salmon

In 2000, the PFMC again enacted restrictive commercial and recreational ocean salmon regulations in California to achieve: (1) the escapement goal for Sacramento River fall chinook salmon (*Oncorhynchus tshawytscha*) of 122,000 to 180,000 hatchery and natural adults combined; (2) a 13.8% exploitation rate on age-4 Klamath River fall chinook salmon to accommodate in-river recreational and tribal subsistence and commercial fisheries, as well as a minimum adult natural spawning escapement of 35,000; (3) a 31% increase in the adult spawner replacement rate for endangered Sacramento River winter chinook salmon relative to the observed 1989–93 mean rate; and (4) a reduction in harvest impacts on depressed coho salmon (*Oncorhynchus kisutch*) stocks coastwide.

In 2000, commercial fishing for ocean salmon (all species except coho) in California was allowed coastwide 1 May to 30 September, with various time and area closures. The minimum size limit was 26 inches (TL), and 27 inches after 30 June to help reduce retention of the generally smaller Sacramento River winter chinook salmon; however, a continuation of the 1999 Bodega Bay test fishery in July maintained a minimum size limit of 26 inches (TL). Approximately 2,050 t (429,200 fish) of dressed chinook salmon were landed by commercial trollers, who fished approximately 17,700 days (fig. 5). Ex-vessel prices for dressed salmon averaged \$1.96 per pound, and the total ex-vessel value of the fishery exceeded \$8.8 million.

Recreational fishing regulations in California were less restrictive than in 1999, with various time and area closures (open 12 Feb.–12 Nov.). Statewide recreational landings increased by almost 105% compared to the previous year (fig. 6), totaling 179,900 chinook salmon during 208,700 angler trips (catch per unit angler = 0.86). Anglers were limited to two salmon per day (all species except coho) with a minimum size limit of 20 inches TL, except that prior to 1 June the minimum size limit was 24 inches TL. Anglers fishing by any means other than trolling in the area between Point Conception and Horse Mountain were required to use only "circle" hooks.

In the Klamath Management Zone (KMZ: Horse

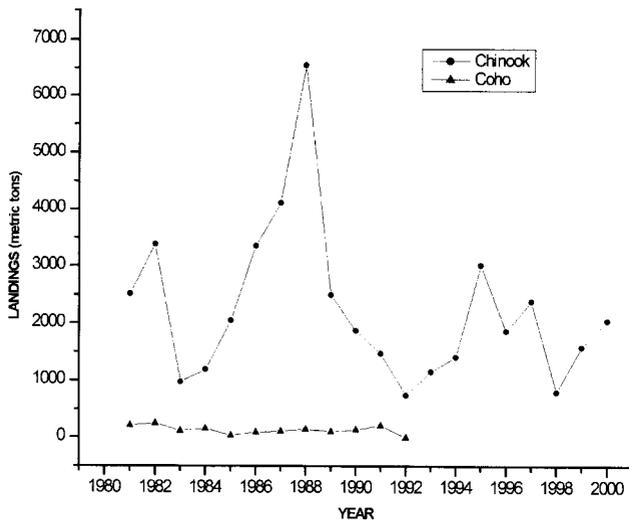


Figure 5. California commercial landings of ocean salmon, 1981–2000.

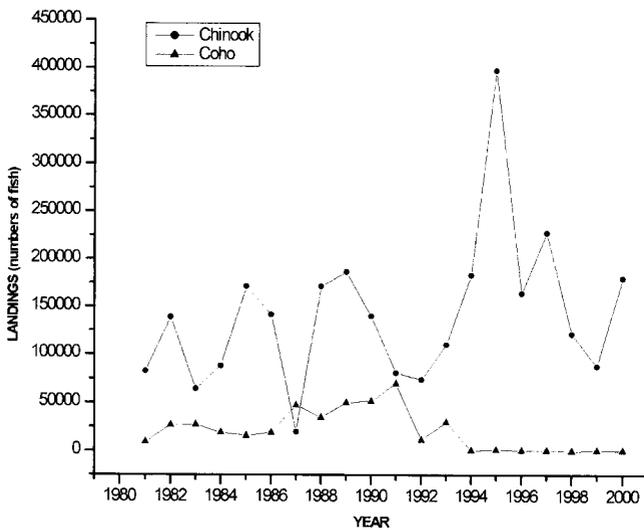


Figure 6. California recreational landings of ocean salmon, 1981–2000.

Mountain, California, to Humbug Mountain, Oregon) season management, rather than quotas, continued, with more fishing days because of increased Klamath fall chinook salmon. In the KMZ, two separate seasons were enacted: (1) 27 May–6 July, and 29 July–10 September, open all days a week. The bag limit was one salmon per day (all species except coho) during the first season and two salmon per day during the second season, with no more than 6 salmon in 7 consecutive days; there was a 20-inch TL limit north of Horse Mountain. In the California portion of the KMZ, anglers landed 13,200 chinook salmon during 20,000 angler trips made primarily on private skiffs.

Pacific Sardine

Increases in the Pacific sardine (*Sardinops sagax*) fishery continued in 2000, with the year's total landings of

57,935 t being the second highest since the reopening of the directed fishery in 1986 (table 3, fig. 7). The 2000 ex-vessel value of the fishery was \$6.3 million, up from \$5.0 million in 1999. Approximately 43% of the 2000 harvest guideline was landed, and the directed fishery remained open until year's end. The Coastal Pelagic Species Fishery Management Plan (FMP) states that the annual sardine harvest guideline is to be allocated two-thirds to southern California (south of San Simeon Point, San Luis Obispo County, to the Mexican border) and one-third to northern California (fig. 1). Based on a 1 July 1999 biomass estimate of 1,581,346 t, the harvest formula generated an initial 2000 southern fishery allocation of 124,527 t and a northern allocation of 62,264 t. Neither of these allocations were taken by the fishery during the 2000 season.

The sardine population biomass (age 1+) as of 1 July 2000 was estimated at 1,182,465 t by means of a modified version of the integrated stock assessment model called catch at age analysis of sardine-two area model (CANSAR-TAM). CANSAR-TAM is a forward-casting, age-structured analysis that uses fishery-dependent and fishery-independent data to obtain annual estimates of sardine abundance, year-class strength, and age-specific fishing mortality for 1983 through 1999. CANSAR was modified to account for the expansion of the Pacific sardine stock northward to include waters off the northwest Pacific coast. Based on the 2000 estimate of total biomass (age 1+) and the formula in the FMP, the 2001 sardine fishery opened on 1 January with a harvest guideline of 134,737 t for the California fishery, 28% less than the 2000 allocation.

The ex-vessel price for sardines remained relatively low in 2000. Prices ranged from \$22 to \$132 per t and averaged \$77 per t. Other important target species for the southern California wetfish fleet include Pacific mackerel (*Scomber japonicus*) and market squid (*Loligo opalescens*) in the winter, and tunas in summer. In northern California, Pacific herring (*Clupea pallasii*) is also an important target species from January to March. Squid and tuna command significantly higher ex-vessel prices than sardines: \$220 per t for market squid and \$240–\$1,600 per t for tuna. During 2000, sardine landings varied by month because of availability, demand, and fleet participation in these other fisheries.

In 2000, most Pacific sardine landings in California were sold to market processors (83%) or to canneries (17%). Of the percentage sold to canneries, approximately 13% were canned domestically for human consumption and 4% were processed for pet food. In December 2000, the last southern California cannery to can sardines for human consumption was bought out. The cannery now produces canned tuna and on occasion cans sardine for human consumption. In northern

TABLE 3
 Landings of Pelagic Wetfishes in California (Metric Tons)

Year	Pacific sardine	Northern anchovy	Pacific mackerel	Jack mackerel	Pacific herring	Market squid	Total
1977	5	99,504	5,333	44,775	5,200	12,811	167,628
1978	4	11,253	11,193	30,755	4,401	17,145	74,751
1979	16	48,094	27,198	16,335	4,189	19,690	115,542
1980	34	42,255	29,139	20,019	7,932	15,385	114,764
1981	28	51,466	38,304	13,990	5,865	23,510	133,163
1982	129	41,385	27,916	25,984	10,106	16,308	121,828
1983	346	4,231	32,028	18,095	7,881	1,824	64,405
1984	231	2,908	41,534	10,504	3,786	564	59,527
1985	583	1,600	34,053	9,210	7,856	10,275	63,577
1986	1,145	1,879	40,616	10,898	7,502	21,278	83,318
1987	2,061	1,424	40,961	11,653	8,264	19,984	84,347
1988	3,724	1,444	42,200	10,157	8,677	36,641	102,843
1989	3,845	2,410	35,548	19,477	9,046	40,893	111,219
1990	2,770	3,156	36,716	4,874	7,978	28,447	83,941
1991	7,625	4,184	30,459	1,667	7,345	37,388	88,668
1992	17,946	1,124	18,570	5,878	6,318	13,110	62,946
1993	13,843	1,954	12,391	1,614	3,882	42,708	76,392
1994	13,420	3,680	10,040	2,153	2,668	55,395	85,929
1995	43,450	1,881	8,667	2,640	4,475	70,278	131,391
1996	32,553	4,419	10,286	1,985	5,518	80,360	135,121
1997	46,196	5,718	20,615	1,161	11,541	70,257	155,488
1998	41,056	1,457	20,073	970	2,432	2,709	68,646
1999	58,725	5,179	9,527	963	2,432	90,322	164,945
2000	57,935	11,396	21,053	1,126	3,724	117,686	212,920

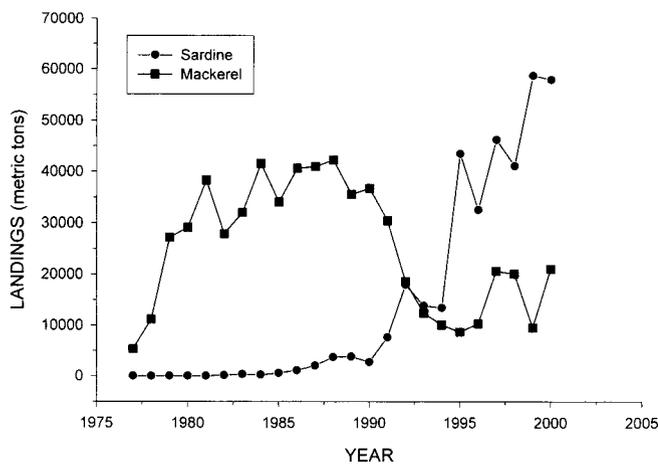


Figure 7. California commercial landings of Pacific sardine and Pacific mackerel, 1977–1999.

California, one cannery continues to can fish for human consumption.

Currently, sardines are processed for human consumption (fresh or canned), pet food, or export. Most of the exports are sold for human consumption or used as feed in aquaculture facilities. Approximately 71% of California's sardine landings were exported in 2000, primarily (95%) as frozen blocks. In 2000, 41,172 t of sardines were exported, up from the 1999 total of 36,089 t. Export revenues totaled \$23.33 million at approximately \$567 per t. Australia is the major importer of sardines for fish food in aquaculture facilities, while Japan

continues to be a large market for sardine for human consumption after the failure of its own sardine fishery.

Aside from the wetfish fishery for sardine, there is a small live bait fishery that is not subject to a harvest guideline and usually takes less than 5,000 t per year. In 2000, the ex-vessel value of the sardine live bait fishery was approximately equal to that of the directed fishery.

Pacific Herring

Pacific herring (*Clupea pallasii*) fisheries for 2000 continued their recovery from the devastating effects of the 1997–98 El Niño. Statewide landings for the 1999–2000 sac roe season (December–March) totaled 3,058 t, a 16.0% increase from the previous season's landings of 2,637 t. Annual sac roe landings increased from 2,207 t to 3,724 t, up 59.3% from the previous year (table 3). Success of the sac roe fisheries continued to be mixed. The San Francisco gill net fleet, composed of three platoons (428 permits), landed 3,051 t, 38.5% under the 4,964 t quota. The Tomales Bay fishery landed a total of 38 t of the 364 t quota. A total of 6.5 t was landed in Crescent City from the 27 t quota, and Humboldt Bay landings totaled 1 t, 2% of the 49 t quota.

Ex-vessel prices for herring with 10% roe recovery averaged about \$800 per short ton for gill net landings, with an additional 10% of the base price paid for each percentage point above 10%. The ex-vessel price per ton was higher than in the previous season, reflecting confidence in an improving Japanese economy. Statewide ex-vessel value of the sac roe fishery was an estimated

\$3.8 million, a 35.7% increase from last season; however, this was well below the average for the previous fifteen seasons (\$9.5 million).

For the third consecutive season, the San Francisco Bay herring eggs-on-kelp fishery landings were well below average. Landings totaled 31 t, 34.4% less than the 90.2 t quota, and the second lowest total on record. Total estimated value of the 1999–2000 eggs-on-kelp harvest was \$470,000, based on an estimated ex-vessel price of \$7.00 per pound—approximately \$2.00 more than prices paid in the previous season. The cost of processing was higher, thus landing marginal product was economically infeasible. As in the 1998–99 season, permittees reported that giant kelp (*Macrocystis pyrifera*) lasted longer while suspended because of higher salinities in the bay; higher salinities were probably due to the lack of early winter storms.

Hydroacoustic and spawn-deposition surveys were conducted by the CDFG to estimate herring spawning biomass in San Francisco Bay. Spawn-deposition estimates were used exclusively to assess the Tomales Bay population. No surveys were conducted for Humboldt Bay or Crescent City Harbor. The 1999–2000 herring spawning biomass estimate for the San Francisco Bay population was 24,909 t, a decline of 44.2% from the previous season. Although there was a return to favorable oceanic conditions, and returning herring were in good physical condition, an apparent displacement or loss of older year-class fish (5-year-olds and older) contributed to an unexpected decline in the spawning biomass. Younger herring (2-, 3-, and 4-year-olds) constituted 89% of the biomass.

The Tomales Bay herring spawning biomass continued its tendency to fluctuate widely. The 1999–2000 spawning biomass estimate was 1,828 t, about one-half of the previous season's 3,699 t biomass. The 1999–2000 biomass was well below the 25-year long-term average of 4,343 t, and 25% less than the 7-year average of 2,435 t since the Tomales Bay herring fishery reopened in the 1992–93 season. Length-at-age samples from the 1999–2000 season suggest that age groups 4 and older decreased from the 1998–99 season.

Favorable ocean conditions continued with the prevailing La Niña, and herring fisheries were expected to improve in the 2000–2001 season. But the December fishery in San Francisco Bay opened with limited success. High salinities and cold water temperatures in the bay may have influenced spawning activity, although sampled herring were in good physical condition and showed normal gonadal development.

Kazunoko remains an integral part of traditional Japanese New Year's festivities. However, continuing volatility in the Japanese economy and changes in the Japanese culture have affected the sac roe market. Industry ob-

servers predict that demand for kazunoko will wane as younger Japanese become more Westernized. Ex-vessel prices are expected to decline with concern for the Japanese economy, and herring buyers were proceeding cautiously and offering lower prices than in the 1999–2000 season.

Pacific Mackerel

The 2000 annual landings of Pacific mackerel (*Scomber japonicus*) in California totaled 21,053 t, a 121% increase from the 1999 total of 9,527 t (table 3, fig. 7). Effort was focused on traditional fishing grounds from Monterey south to the U.S./Mexican border. Ninety-seven percent of the landings were made in southern California, primarily at San Pedro and Terminal Island. Monterey landings typically range from 1,000 to 3,000 t per year but were negligible in 2000 because cold oceanic conditions decreased mackerel availability to the northern California fishery.

On the basis of an estimated biomass of 239,286 t on 1 July 1999, the CDFG did not establish a quota for the first half of the 1999–2000 season. On 1 January 2000, management authority for Pacific mackerel was transferred from the CDFG to the National Marine Fisheries Service through the Pacific Fisheries Management Council under the Coastal Pelagic Species Management Plan (FMP). After the transfer of authority, the PFMC used the CDFG biomass estimate to set a harvest guideline of 46,428 t for the period beginning 1 July 1999. The 3,609 t estimated harvest of Pacific mackerel between 1 July 1999 and 31 December 1999 was subtracted from the harvest guideline; therefore, the harvest guideline available to the fishery beginning 1 January 2000 was 42,819 t. Between 1 January 2000 and 30 June 2000 only 3,196 t were landed, 62% in June, when schools of large fish appeared off southern California. The season closed with 39,623 t of the harvest guideline remaining.

Based on an estimated biomass of 128,898 t on 1 July 2000, the PFMC set the harvest guideline at 20,740 t for the 2000–2001 season. The 1 July 2000 biomass estimate was derived from a tuned virtual population analysis (VPA) model called ADEPT and from certain assumptions about recruitment in January of 1999 and fishing mortality during the first half of 2000. The maximum sustainable yield control rule for Pacific mackerel specified in the Coastal Pelagic Species Fishery Management Plan (Amendment 8) was used to calculate the 2001 harvest guideline.

After more than a year of scarce mackerel landings, relatively large mackerel appeared off southern California during the summer of 2000, and the fleet landed 19,617 t (95% of the harvest guideline) by October. Because the harvest guideline includes incidental landings of mack-

erel, the directed fishery for Pacific mackerel was closed on 27 October 2000, with 952 t left of the harvest guideline. An incidental harvest of up to 20% by weight of Pacific mackerel in landings of other species was in effect until the harvest guideline of 20,740 t was reached on 12 March 2001. After 27 March, only 1 ton was allowed per load. This closure will remain in effect until the beginning of the fishing season on 1 July 2001.

The ex-vessel price paid for Pacific mackerel (landings over 1 t) ranged from \$44 to \$882 per t, with an average of \$154 per t. The sale of the catch generated approximately \$2.75 million paid to fishermen. The majority of landings less than one t were sold to small specialty markets and dealers. The ex-vessel price for these landings ranged from \$22 to \$4,410 per t, with an average of \$926. Although these landings totaled only 110 t, they generated approximately \$64,000.

Approximately 10,200 t (48%) of California's Pacific mackerel landings were exported in 2000, up from the 1999 total of 1,915 t. Export revenues totaled approximately \$4.0 million.

Nearshore Live-Fish

Nearshore finfish species are those found within 3 miles of shore and in waters shallower than 40 fathoms. These nearshore species are primarily found in association with kelp beds or on rocky reefs. In accordance with the Marine Life Management Act (MLMA) of 1998, the California Department of Fish and Game is in the process of developing a management plan for the nearshore finfish fishery.

This review focuses on the nearshore finfish species most commonly captured and sold live. Many of the nearshore species targeted by the premium live-fish fishery are territorial, slow-growing, and long-lived, which makes them vulnerable to overfishing even at low exploitation rates. Recognition of these important factors was a key reason for developing the Marine Life Management Act. The MLMA mandates the development and enactment of a Nearshore Fishery Management Plan by the beginning of the year 2002 to insure continued viability of these nearshore species at sustainable yield levels. The Nearshore Fishery Management Plan will include a total of 19 species which the CDFG has identified as the nearshore finfish species in need of immediate management attention. These are cabezon, California scorpionfish, California sheephead, kelp and rock greenlings, monkeyface prickleback, and the following rockfish: black, black-and-yellow, blue, brown, calico, China, copper, gopher, grass, kelp, olive, quillback, and treefish. The above 19 species represent the most common species in the nearshore live-fish fishery. All but three (California sheephead, monkeyface prickleback, and rock greenling) of the 19 species are designated as

groundfish under the PFMC's fishery management plan for Pacific coast groundfish.

The Nearshore Fishery Management Act of 1998 (NFMA) implemented commercial size limits for the following nearshore species: black-and-yellow rockfish, cabezon, California sheephead, China rockfish, gopher rockfish, grass rockfish, greenlings, kelp rockfish, and the California scorpionfish. The NFMA also requires the possession of a Nearshore Fishery Permit to take, possess, or land any of the ten species.

The nearshore live-fish fishery began in the mid-1980s. Initially, the fishery supplied live fish destined for the California Asian community. The live-fish market has expanded since the 1980s and now supplies California markets as well as markets in other states and, in some cases, other countries. The primary gears used in nearshore waters to capture live fish are various hook-and-line methods and trap gear. Hook-and-line gear includes rod-and-reel, vertical longlines, "sticks," and set horizontal longlines.

Before the start of the nearshore live-fish fishery, the price paid to fishermen (ex-vessel value) for rockfishes, cabezon, California sheephead, and greenlings was low, especially in comparison to fish such as salmon and California halibut. Since the development of the live-fish fishery, fish buyers and consumers have been willing to pay much higher prices. For example, the average ex-vessel value of cabezon was less than \$.50 per pound in 1989, but was \$3.63 per pound in 2000. The target species and the fishing methods of the current fishery are driven by this demand for high-quality, fresh, live fish. In 2000, the ex-vessel value for live fish was approximately \$2.5 million.

Landing receipts, also commonly called market receipts, are the primary source of data used to describe commercial fishing activity. By law, a fish buyer must complete a landing receipt at the time fish are delivered. The buyer must provide data for each transaction and include weight of the fish landed, price paid to the fishers, and the condition of the fish (e.g., live). Fish are recorded as market categories rather than under species-specific names. This often means that a particular market category (e.g., China rockfish) may actually contain several different species. In the nearshore fishery, fish that have been landed live are not always recorded as live on the landing receipt. In such cases it can be difficult to discern live landings from dead landings. Sometimes, price per pound serves as an indicator of fish condition: a higher price can indicate a live fish. Because of this discrepancy, landing weights given in this review should be assumed to be low estimates of the actual live-fish landing weights. It should also be noted that the condition (live or dead) of fish being landed was not required on landing receipts prior to 1993. Therefore, data used

in this text generally refer to the period from 1993 through 2000.

Several regional differences exist in the nearshore live-fish fishery. Many of these are due to the fact that several of the 19 species have different geographic ranges. South of Point Conception, California sheephead and California scorpionfish are the primary species landed live. In central California, from Point Conception to Cape Mendocino, the species composition of the live-fish landings is more diversified. While the "group bolina" (consisting mostly of brown rockfish) is the most common market category, landings of several other market categories such as cabezon, kelp greenling, black rockfish, blue rockfish, and China rockfish are also reported for central California.

The year 2000 was the first year that the PFMC put into place a regularly scheduled two-month fishery closure for all nearshore rockfish. South of Lopez Point (Monterey County), taking nearshore rockfish was prohibited during January and February. Between Lopez Point and Cape Mendocino (Humboldt County), taking nearshore rockfish was prohibited during March and April. There was no closed season north of Cape Mendocino. In January 2000, a two-month cumulative limit for nearshore rockfish (defined by PFMC as the 13 rockfish species listed above and California scorpionfish) was set at 2,400 pounds for limited entry fixed gear permits north of Cape Mendocino, and 1,000 pounds south of Cape Mendocino. The open access fishery two-month cumulative limits were set at 1,000 pounds north of Cape Mendocino and 550 pounds south of Cape Mendocino.

Although final landings data from commercial landing receipts for the nearshore live-fish fishery have not yet been tallied for the 2000 season, it is expected and evidenced in preliminary summaries that the closures and two-month cumulative limits did indeed lower the annual harvest of all nearshore rockfish species. However, landings of live nearshore rockfish species decreased only slightly in 2000 (fig. 8) and consequently accounted for 76% of the overall nearshore catch. In the previous seven years since the CDFG has been recording live landings, the next highest percentage of live fish in nearshore species landings was 58% in 1999. This was most likely because fishermen could not land as many total nearshore rockfish in 2000 and therefore sought to sell what they could land in live condition, thereby receiving a higher price per pound.

CDFG observations have shown that during the rockfish closures, fishing effort in some areas was shifted toward other nearshore species that can be marketed live. One such example are the surfperch (Embiotocidae) in the San Francisco port area. Although surfperch have been commonly landed commercially in the area for the past several years, they were marketed primarily live only

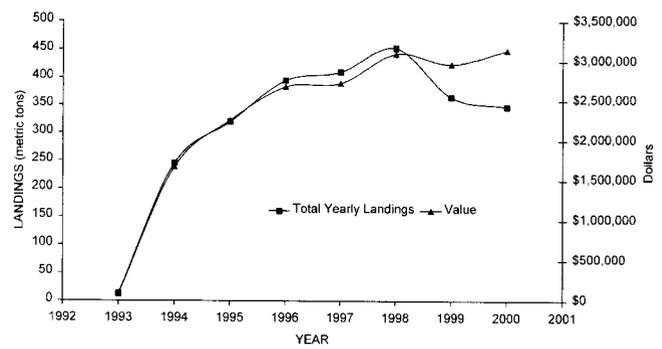


Figure 8. California nearshore live-fish landings, 1993–2000.

during and after the PFMC two-month rockfish closures. Presumably, fishers and dealers needed to sell the surfperch live (at premium prices) to make up for profit losses due to the rockfish closures.

Although total landing weight of live nearshore finfish declined slightly in 2000 (346 t), landings have remained relatively high over the past several years since the dramatic increase in the live-fish fishery in the early 1990s (fig. 8). The value of the nearshore live-fish fishery has continued to increase since the beginning of the fishery; 1999 and 2000 were the first years in which the value of the fishery continued to increase while annual landings decreased (fig. 8). This is presumably because live fish reach higher and higher ex-vessel values as supplies decrease because of environmental factors, depleted stocks, and regulatory changes. Given this scenario, it is likely that the percentage of nearshore finfish marketed live will remain high and possibly continue to increase.

There were 618 vessels landing nearshore fish species in 2000. The number of hook-and-line vessels landing nearshore species peaked in the early 1990s (at 1,138 vessels in 1990) and has declined by approximately 43% since 1990. Throughout the period from 1990 through 2000, more than half the vessels landed less than 1,000 pounds of nearshore fish per year, with from 16% to 22% landing less than 100 pounds. Most vessels (85%–92%) made fewer than 25 landings per year. Presumably, many of the smaller landings were primarily live fish. Most of the hook-and-line and trap vessels (which account for most of the live fish landed) used in the nearshore region ranged from 20 to 39 feet in length.

As the nearshore live-fish fishery continues, and in some port areas increases, there is a real potential for localized depletion of targeted fish stocks. Conflicts among user groups are also a major concern, particularly as the issue of resource allocation among groups is discussed by fishery managers and constituents involved in the development of the Nearshore Fishery Management Plan. There is a clear need to determine accurate fishing patterns on both temporal and spatial scales. Developing

TABLE 4
 California Commercial Halibut Landings (Metric Tons)

Port	1999			2000*		
	Catch (t)	Percentage of catch	Value (\$)	Catch (t)	Percentage of catch	Value(\$)
Eureka	2.95	0.5	13,027	0.421	0.11	2,016
Fort Bragg	0	0	0	0.476	0.12	150
Bodega Bay	10.89	1.8	54,615	6.84	1.8	41,818
San Francisco	203.53	34.19	1,052,119	126.57	33.36	731,298
Monterey	90.16	15.15	368,063	20.61	5.43	101,754
Morro Bay	35.16	5.91	187,792	18.23	4.81	109,789
Santa Barbara	134.62	22.62	808,956	94.86	24.99	620,640
Los Angeles	99.33	16.7	673,155	86.48	22.79	630,617
San Diego	18.6	3.13	114,589	24.96	6.59	175,108
Totals	595.24	100	3,272,316	379.53	100	2,413,190

*Preliminary data

TABLE 5
 CPFV Landings of California Halibut (Numbers of Fish Caught), 1993–2000

Location	Year							
	1993	1994	1995	1996	1997	1998	1999	2000*
State total	5,335	7,549	19,345	19,092	15,574	12,191	14,339	15,328
N. California	1,449	4,134	13,664	13,263	7,964	7,357	5,054	5,098
S. California	3,886	3,415	5,681	5,289	7,880	4,834	9,285	10,230

*Preliminary data

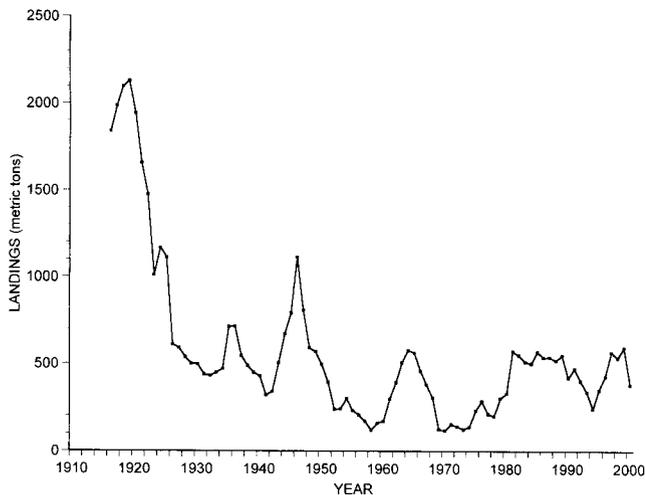


Figure 9. California commercial landings of California halibut, 1916–2000.

indices of abundance is also likely to become a top priority among fishery managers and researchers hoping to promote a sustainable nearshore fishery.

California Halibut

Commercial landings of California halibut (*Paralichthys californicus*) totaled approximately 380 t in 2000 (table 4), a 36% decrease from the 595 t landed in 1999 (fig. 9), which was the highest yearly landing since 1947. Except for a small decline 1998, landings in 2000 marked the end of an upward trend that began in 1995. Northern

California ports dominated halibut catch statewide from 1995 to 1999.

San Francisco led the state in halibut landings, with 33% of the total catch by weight, followed by Santa Barbara (25%), and Los Angeles (23%). Halibut landings decreased at all ports except Fort Bragg and San Diego; only 41% of the landings came from Monterey and ports to the north, compared to 52% in 1999. The shift in landings to more southerly ports reverses a trend that began with the statewide increase in commercial halibut landings in 1995. However, there is some evidence from sport fishery data to indicate the reemergence of the northern California ports' dominance.

The 1995 statewide increase in commercial halibut landings was echoed by the increased sport catch of halibut by commercial passenger fishing vessels (CPFVs; table 5) and other recreational modes of sportfishing (table 6). During the dramatic 1995 increase, the greatest portion of the catch came from northern California. Unpublished CDFG halibut creel survey data from northern California in 1995 showed a very large year-class of halibut approaching sport and commercial legal size (22 in). On the basis of published growth rates for California halibut, this was estimated to have been the 1992 year-class. El Niño conditions existed along much of the California coast in 1992, possibly conducive to good reproductive success for halibut in northern California and beyond. Little subsequent recruitment of halibut in northern California was detected by sport creel

TABLE 6
 Estimated Annual Catch (Fish Kept) in Thousands of California Halibut
 by Marine Recreational Anglers for All Modes of Fishing in All Marine Areas

Location	Year							
	1993	1994	1995	1996	1997	1998	1999	2000*
State total	66	104	337	147	92	106	130	165
N. California	31	52	267	87	46	44	25	59
S. California	35	52	70	60	46	62	105	106

Source: Marine Recreational Fisheries Statistics Survey
 *Preliminary data

TABLE 7
 Yellowfin Tuna Prices by Gear Type, 2000

Gear	Price per pound (\$)			Average/metric ton (2,240 lbs)	Total pounds
	Average	Minimum	Maximum		
Hook-and-line	1.20	0.50	1.75		11,309
Trawl	1.16	0.32	2.00		258
Gill net	1.35	0.50	2.50		1,327
Purse seine	0.66	0.11	1.50	1,478.40	2,436,399

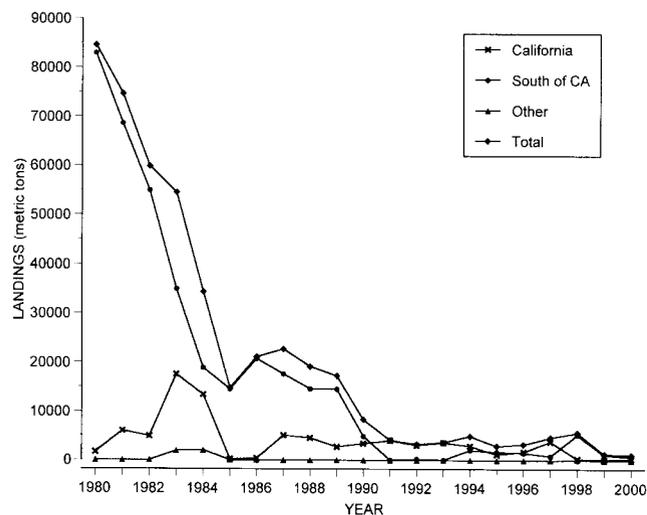


Figure 10. Commercial yellowfin tuna landings, 1980–2000.

surveys or reported by commercial fishermen until 2000, when sublegal halibut (1997 El Niño year-class) were caught and released in large numbers by both commercial and sport fishers.

Total preliminary value for halibut landings in California for 2000 was \$2.41 million. The statewide ex-vessel price per pound for halibut ranged from \$1.00 to \$7.50, with an average of \$2.88 per pound. Ports south of Monterey averaged about \$.50 more per pound than ports to the north, probably because of a more developed live-fish market in southern California. Some northern California commercial fishers landed dressed or bled fish in order to receive a higher price per pound. Total commercial trawl effort for halibut has increased because of increased restrictions on groundfish species. The in-

creased availability of commercial halibut can flood local markets and depress ex-vessel price per pound.

Yellowfin Tuna

Total commercial landings of yellowfin tuna (*Thunnus albacares*) have declined dramatically since 1980, when landings were almost 100 times as high as in 2000 (fig. 10). Much of this decline may be due to the shift in fishing effort and processing to the western Pacific. Commercial landings and imports of yellowfin tuna in 2000 were slightly under 1,140 t. Domestic fishers reported landing 368 t from California waters. Landings from Mexico and areas to the south accounted for 761 t, and landings from other areas accounted for 11 t. One reason for this sharp decline in California waters was that Mexico closed its waters to U.S. fishers in 1981–82. Most of the yellowfin tuna was taken by purse seine vessels, with minor landings from hook-and-line, troll, and longline vessels. Most of the fish were canned; the remainder were delivered to the fresh fish market, where tuna command higher ex-vessel prices of \$240–\$1,600 per ton (table 7).

Yellowfin tuna are occasional visitors to southern California: their presence depends on oceanographic conditions. When there is a strong El Niño event, such as that in 1983, yellowfin tuna can be found in abundance. They are also frequently taken when local warming of the ocean extends from Baja California, Mexico, into southern California. Such episodes can occur independently, yet the local abundance of tuna can match that during El Niño events. The year 2000 was a period of local warming, and yellowfin tuna were relatively abundant in California.

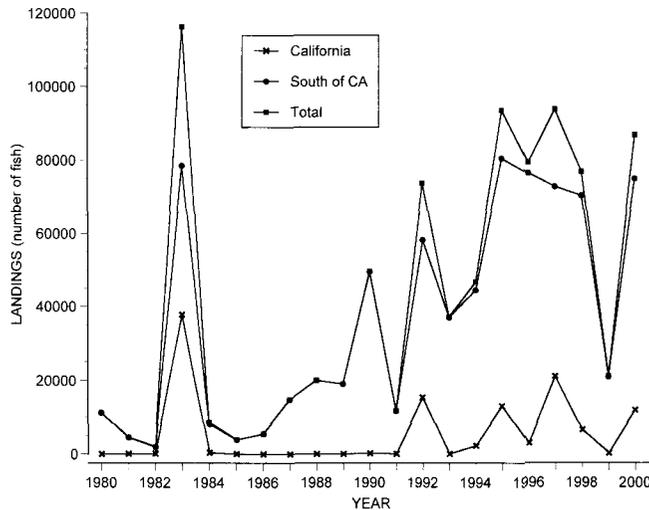


Figure 11. Recreational yellowfin tuna landings, 1980–2000.

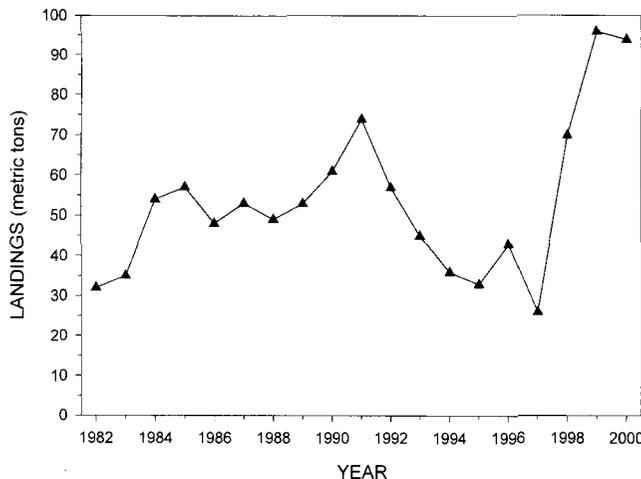


Figure 12. California commercial landings of white seabass, 1982–2000.

Sport anglers operating from California ports landed 119,797 yellowfin tuna in 2000 (fig. 11). Commercial passenger fishing vessels reported catching 11,940 fish in U.S. waters and 74,857 in Mexican waters. Private boat catches for vessels in U.S. waters were estimated by the Marine Recreational Fisheries Statistics Survey (MRFSS) at 33,000 fish. No catch estimates for private boats were available for trips in Mexican waters. Average weights from MRFSS sampling indicate that CPFV anglers landed a minimum 626 t of yellowfin tuna while private boat anglers landed 181 t. These figures represent low estimates, since longer trips, which usually catch bigger fish, were not sampled.

White Seabass

White seabass (*Atractoscion nobilis*) is the largest member of the Sciaenid family harvested from California's nearshore waters and islands. It can grow to 1.5 m and

TABLE 8
 California 2000 Commercial White Seabass Landings

Port	Catch (t)	Ex-vessel value
Los Angeles	45	\$188,630
Santa Barbara	30	\$138,278
Monterey	11	\$46,251
San Diego	7	\$37,237
Morro Bay	2	\$8,070
San Francisco	1	\$5,534

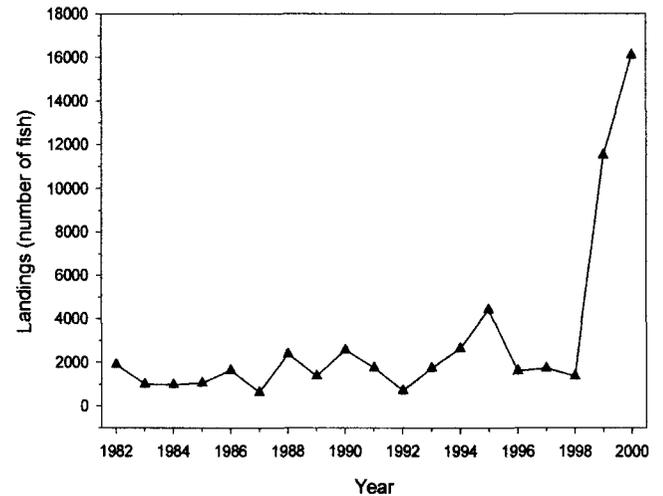


Figure 13. California commercial passenger fishing vessel (CPFV) landings of white seabass, 1982–2000.

weigh 36 kg, making it one of California's premier game fish. The commercial component of this fishery supports a relatively low-volume, high-quality domestic industry.

A summary of CDFG's Commercial Fisheries Information System preliminary data indicates that white seabass landings totaled 96 t in 2000, a 14% decrease from 1999 (fig. 12). Fish markets from San Diego to San Francisco reported white seabass landings; most were made at fish markets south of Point Conception (table 8). Fish dealers paid from \$.50 to \$7.00 per pound for white seabass, for an estimated total annual ex-vessel price of \$424,000. The average price per pound was \$2.20, up \$.29 from 1999, when landings reached an 18-year high.

Over 80% of the commercial landings statewide were made between June and August, following the 15 March–15 June seasonal closure. In 2000, white seabass were harvested primarily by gill net gear: 69% by set gill net and 16% by drift gill net. Additional gears used to harvest white seabass included hook-and-line (14%) and trawl (1%). The percentage of white seabass harvested by hook-and-line gear increased threefold from 1999 to 2000. Premium hook-and-line-caught white seabass commanded the highest price per pound in 2000.

A summary of CPFV logbook data indicated that recreational anglers landed approximately 16,100 white seabass in 2000, up 28% from 1999 (fig. 13). Over 60%

of the reported landings were made between April and August, despite a reduction in the daily bag limit from three to one fish per angler from 15 March to 15 June. Logbook data indicated that most fish (67%) were caught around southern California's Channel Islands; the rest (33%) were taken at isolated spots along the mainland from San Diego to San Francisco.

In the early 1980s, the white seabass population in California appeared to be in decline. In 1983, the California legislature created the Ocean Resources Enhancement and Hatchery Program (OREHP) to perform basic and applied research on the artificial propagation, rearing, stocking, and distribution of adversely affected marine fish species important to sport or commercial fishing in California waters south of Point Arguello. Since 1989, white seabass has been OREHP's primary species for research. Approximately 333,918 OREHP-produced juvenile white seabass were released into the ocean from 1990 through 2000, when 27,845 were released. Each OREHP-produced fish is tagged with coded wire at the hatchery before being transported to a grow-out facility. There are now twelve grow-out facilities located in bays and marinas from San Diego to Santa Barbara, including Catalina Island. The fish are raised by volunteers until they reach 200 mm, and then released from the grow-out site or nearby. As of May 2001, only four legal-size (711 mm) OREHP-produced fish are known to have recruited into the white seabass fishery.

Under the authority of the Marine Life Management Act of 1998, the CDFG is revising the original white seabass FMP submitted to the Fish and Game Commission and the state legislature in 1996 for adoption as a management tool. At that time, the FMP required the approval of both the commission and the legislature before it could be implemented. The commission adopted the FMP as a management tool, but the legislature did not, so the plan was not implemented. The current FMP is being revised according to the guidelines outlined in the MLMA. One of the key aspects of the 1998 act was the transfer of regulatory authority over most commercial fisheries from the legislature to the commission. The revised white seabass FMP is due to the commission in June 2001 for adoption by 1 January 2002.

KELP

Giant kelp (*Macrocystis pyrifera*) has been commercially harvested along the California coast since the early 1900s. It was initially harvested for potash and acetone for use in manufacturing explosives during World War I. The Kelco Company (now ISP Alginates Inc.) began harvesting in 1929 and processing giant kelp for algin, which is used in a wide variety of food processing, pharmaceutical, and manufacturing operations. Revenues generated from algin manufactured in California by ISP

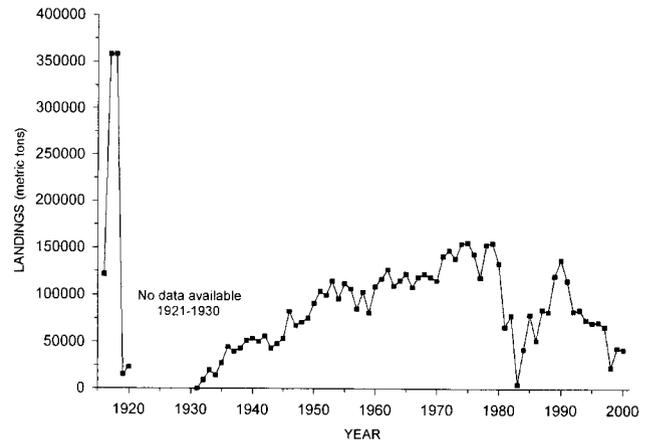


Figure 14. California harvest of giant kelp, 1916–2000.

Alginates during the 1990s were approximately \$40 million annually. In 2000, the algin industry accounted for approximately 92% of the total harvest, and total landings in California were 41,913 t (fig. 14). Giant kelp is also harvested for abalone food by the abalone aquaculture industry, and spawning substrate is harvested by the herring-roe-on-kelp fishery. Recreational users harvest kelp for food, basket making, ceramic art, and compost. The estimated annual harvest by recreational users is less than 0.1% of the total harvest.

Giant kelp is harvested in California state waters from the U.S./Mexico border north to Monterey Bay. There are 88 designated kelp beds statewide, 34 of which are open to harvest by anyone possessing a valid kelp-harvesting permit. Specific beds may be leased for up to 20 years, but no more than 25 square miles or 50% of the total kelp bed area may be leased by any single harvester. The CDFG has designated 34 beds as nonleasable to ensure that smaller harvesters will have access to kelp and not be shut out by lease agreements. In addition to the purchase of a kelp-harvesting permit, regulations require that harvesters cut kelp no deeper than 1.2 m below the surface, and weigh and report the amount they harvest by date and bed number. Kelp harvesters paid approximately \$79,000 in royalties to the CDFG in 2000, or \$1.71 per ton of wet kelp harvested.

Annual harvests have varied considerably, from a high of nearly 360,000 t in 1917–18 to less than 900 t in the early 1930s (fig. 14). The annual harvest during the 1970s averaged nearly 136,000 t, whereas in the 1980s the annual average was only 72,800 t. This decline was due to the intense El Niño of 1982–83 and the “200-year storm” in January 1988, both of which destroyed much of the existing canopies in southern and central California. The steep decline in landings since 1990 is due primarily to changes in the world sodium alginate market and is not a result of reduced kelp canopies. In response to increased competition from overseas harvesters, ISP Alginates

streamlined its California production strategy and shifted its emphasis toward high-quality algin products. As a result, ISP Alginates has reduced its kelp harvest in California waters by nearly 50% since 1990.

ISP Alginates operates several kelp-harvesting vessels ranging in length from 43 to 49 m and capable of harvesting up to 544 t of wet kelp in one day. The abalone aquaculture industry harvests kelp with a variety of vessels ranging from small skiffs to a modified 18 m U.S. Navy landing craft. North of the Monterey Peninsula, kelp is harvested primarily by hand from small skiffs.

In the year 2000 biologists studied the results of the 1999 kelp fly-over to repeat assessments made in 1967 and 1989. The total area occupied by kelp canopy decreased from approximately 70 square miles in 1967 to 40.7 in 1989 and 17.8 in 1999. Kelp canopies throughout the state have declined, particularly those in southern California. This decline can be attributed to both natural disturbances such as warm-water stress and intense storms associated with El Niño, and human-caused disturbances such as increased turbidity and siltation associated with coastal development, pollution, and fishing activities. Commercial and recreational fishers remove animals such as California sheephead and California spiny lobster, which help sustain kelp forests through trophic interactions.

Bull kelp (*Nereocystis luetkeana*) is another commercially important species. Unlike the perennial giant kelp, bull kelp is an annual that grows in the cool, nutrient-rich waters of northern and central California. Bull kelp is harvested primarily by the abalone mariculture industry for abalone feed, although small amounts are harvested incidentally by the algin industry and for human consumption. Bull kelp accounts for a tiny fraction (<1%) of the total kelp harvested in California waters, mainly because it has low algin content and is considered inferior to giant kelp for abalone feed.

The CDFG has recently completed an environmental review of giant and bull kelp commercial and sport harvesting regulations. As a result of this review, and based on public and interagency input, a number of amendments to the regulations governing the commercial harvest of kelp have been adopted. The more substantial amendments include (1) requiring harvesters to obtain Fish and Game Commission approval of a harvest plan before a mechanical harvester can be used for giant kelp in central and northern California; (2) adding a seasonal closure (1 April–31 July) for harvesting bull kelp from open beds that lie partially or totally within the boundary of the Monterey Bay National Marine Sanctuary; (3) increasing the number of beds closed to harvest; (4) closing a portion of a bed in Monterey County that experiences heavy seasonal harvest pressure; and (5) creating a mechanism for restricting harvest by imposing temporary harvest controls where necessary for resource protection.

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Contributors:

S. Crooke and M. Larson, yellowfin tuna

M. Erickson, ocean salmon

P. Haaker and I. Taniguchi, white abalone

P. Kalvass, sea urchin

C. Kong, market squid

T. Moore, California halibut

J. O'Brien, kelp

K. Oda, Pacific herring

D. Ono, spot and ridgeback prawn

V. Taylor, Pacific mackerel, Pacific sardine

D. Thomas, groundfish

K. Walters, nearshore live-fish

S. Wertz, white seabass

THE STATE OF THE CALIFORNIA CURRENT, 2000–2001: A THIRD STRAIGHT LA NIÑA YEAR

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ABSTRACT

This report is the eighth in a series that describe recent oceanographic observations within the California Current system, from Oregon to Baja California. The emphasis here is placed on the observations conducted concurrently by the CalCOFI (California Cooperative Oceanic Fisheries Investigations), IMECOCAL (Investigaciones Mexicanas de la COrriente de CALifornia), and GLOBEC-LTOP (GLOBal Ecosystems Long-Term Observation Program) programs from April 2000 to January 2001. The large-scale oceanic and atmospheric conditions over the tropical Pacific indicated a third straight La Niña year. Coastal conditions exhibited weaker than normal upwelling off northern Baja California and southern California through 2000 and early 2001. Measurements off Oregon, southern California, and Baja California denoted oceanographic conditions near the climatological norm. Likewise, zooplankton biomass decreased from the high levels observed in 1999 to nearly normal values, while cold-water species of seabirds did not increase off southern California. A return to more

normal levels of the monitored features of the CCS does not yet support the idea of a climate regime shift.

INTRODUCTION

This is the latest in a continuing series of reports that describe and outline recent observations of the physical and biological structure of the California Current system (CCS). In this report we concentrate on observations conducted from April 2000 to January 2001 along the CalCOFI (southern California) and IMECOCAL (Baja California) survey regions. We also include information from several other programs in order to put these programs into a larger regional context.

Previous reports in this series have brought into perspective the evolution of oceanographic conditions within the CCS, from the conditions prior to (Hayward et al. 1994, 1995, 1996; Schwing et al. 1997) and during El Niño 1997–98 (Lynn et al. 1998). The number and diversity of programs along the CCS have allowed the 1997–98 El Niño, one of the strongest on record, to be one of the most extensively documented by a series of regional oceanographic programs ranging from Baja California to British Columbia (Chavez et al., in press; Collins et al., in press; Huyer et al., in press; Lynn and

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TABLE 1
 Locations of SST and Alongshore Wind Time Series

Buoy	Name	Position	Base period ^a	Alongshore angle (°N) ^b
46050	Stonewall Bank, Ore.	44.6°N 124.5°W	1991–99	359
46027	St. George, Calif.	41.8°N 124.4°W	1983–99	341
46022	Eel River, Calif.	40.8°N 124.5°W	1982–99	354
46042	Monterey Bay, Calif.	36.7°N 122.4°W	1987–99	328
46011	Santa Maria, Calif.	34.9°N 120.9°W	1980–99	325
46025	Catalina Ridge, Calif.	33.7°N 119.1°W	1982–99	295

^aPeriod of harmonic mean.

^bDetermined from principal-component analysis.

Bograd, in press; Schwing et al., in press; Durazo and Baumgartner MS).² A good example of this monitoring can be seen in Castro et al. (in press), a hydrographic atlas of data collected along the west coast of North America between January 1997 and January 1999.

The demise of the 1997–98 El Niño was followed by a transition to a cold episode, as reflected by a number of environmental indices (Wolter and Timlin 1998; Schwing et al.³). Hayward et al. (1999) have shown how this transition period, which was characterized by a strengthening of the North Pacific High, eventually led to stronger than normal coastal upwelling and a decrease in sea level, a regime typical of La Niña. Upwelling during spring 1999 was the strongest on record (Schwing et al. 2000). Furthermore, Bograd et al. (2000) described how these conditions persisted throughout the period from spring 1999 to spring 2000. Since last year's report and at the time of this writing (May 2001), the persistent pattern of stronger than normal low-level easterlies over the central equatorial Pacific, which has been characteristic of La Niña conditions since mid-1998, has continued for 33 consecutive months. Despite small differences in their predictions, the most recent model forecasts point toward a weakening of La Niña and a return to normal conditions for summer 2001, as well as a trend to slightly positive anomalies by 2002.

Observations made between April 2000 and January 2001 are used here to describe the oceanographic conditions over the CCS, to explore the system's response to the lingering La Niña, and to contrast these observations with the long-term means. We begin by analyzing the large-scale atmospheric and oceanic conditions for the period, putting special emphasis on the northeastern Pacific; we continue our description by examining the coastal and oceanographic conditions along the CCS, roughly from 26°N to 45°N, and by examining the biological response to the oceanic conditions that force

the variability in the California Current. We complete our discussion by bringing out the importance of concurrent measurements along the CCS and the need for more systematic, long-term monitoring of the biophysical coupling within the limits of the CCS.

DATA SETS AND METHODS

The observations presented here were obtained from fixed (buoys) and moving (ships, drifters) platforms. Time series of the daily alongshore wind component and sea-surface temperature (SST) observations for six geographical regions of the CCS are obtained from buoys operated by the NOAA National Data Buoy Center (NDBC); the location and base period of each buoy is given in table 1. Monthly upwelling indices and their anomalies, relative to the 1948–67 mean, for the western North American coast are presented. The indices estimate the intensity of large-scale, wind-induced coastal upwelling and are based on the descriptions of Schwing et al. (1996).

The CalCOFI program monitors the oceanographic conditions off southern California on quarterly surveys (normally January, April, July, and October) that occupy a grid of 66 stations (fig. 1). Routine station activity includes CTD/rosette casts to 500 m depth, with sensors for pressure, temperature, salinity, dissolved oxygen, photosynthetically active radiation, fluorescence, and transmissivity. Water samples are collected at 20–24 depths to determine salinity, dissolved oxygen, nutrients (NO₃, NO₂, PO₄, SiO₃), phytoplankton pigments (chlorophyll *a* and phaeophytin), and primary production (¹⁴C uptake at one station per day). Oblique and surface (neuston) net tows (0.505 mm mesh) are taken at each station. Continuous underway sampling of temperature and salinity are carried out, and high-resolution measurements of upper ocean currents are made with an acoustic Doppler current profiler (ADCP). During the winter and spring cruises, the continuous underway fish egg sampler (CUFES; Checkley et al. 1997) is used. Vessel-based (CalCOFI) and colony-based (PRBO) seabird observations between spring 1999 and spring 2001 are placed in perspective by relating them to existing long-

²Durazo, R., and T. Baumgartner. MS. Evolution of oceanographic conditions off Baja California: 1997–1999.

³Schwing, F. B., T. Murphree, and P. M. Green. MS. A climate index for the northeast Pacific.

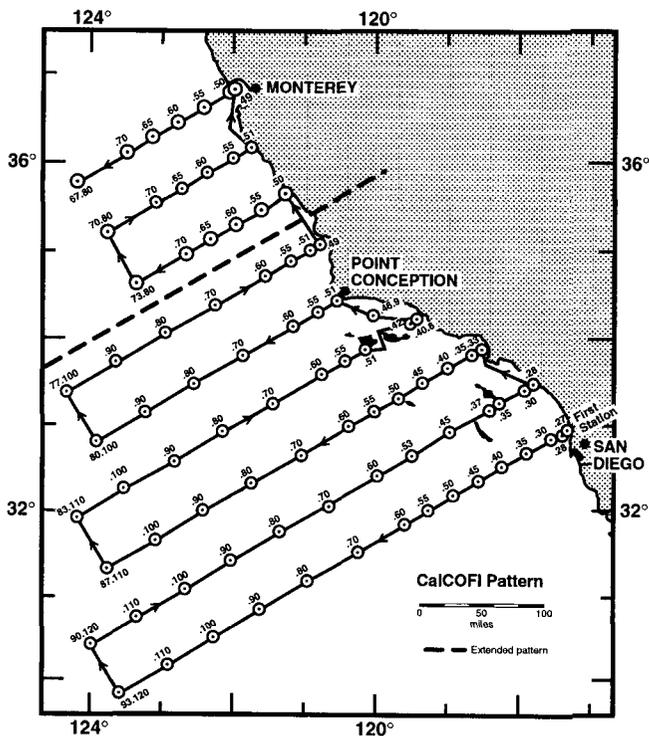


Figure 1. The standard CalCOFI sampling grid. The regular 66-station pattern occupied by CalCOFI since 1985 (lines 77, 80, 83, 87, 90, and 93) is shown by a solid line. The area of additional underway sampling north of the regular pattern is above the dashed line (lines 67, 70, and 73).

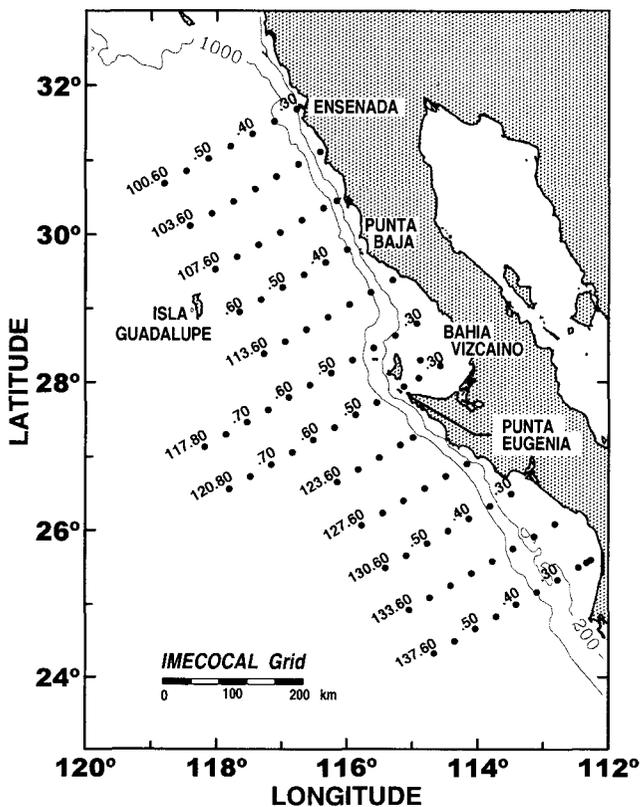


Figure 2. The standard IMECOCAL sampling grid. The regular 93-station pattern (lines 100 to 137) is shown by solid circles. The 200 and 1,000 m depth contours are included.

term data sets. Our objective was to determine whether marine bird at-sea abundance and demography reflected enhanced upwelling and elevated ocean productivity recorded since the winter of 1999 (Bograd et al. 2000; Schwing et al. 2000).

The IMECOCAL program continued sampling the southern region of the California Current, off Baja California, on a reduced CalCOFI grid of 93 stations (fig. 2). The sampling includes CTD casts to 1,000 m, bottom depth permitting, as well as water samples from the upper 200 m to determine dissolved oxygen, nutrients, chlorophyll *a*, and primary production (one ^{14}C “in situ” incubation per day). Standard (.505 mm mesh) oblique bongo tows are conducted, with one cod end dedicated to ichthyoplankton and the other to macrozooplankton. Continuous underway measurements of temperature, salinity, and fluorescence are also made; the ADCP was used for continuous current profiling. Starting in January 2000, a CUFES system (Checkley et al. 1997) has been incorporated into the sampling, and preliminary results are presented below.

We also present data from the U.S. GLOBEC Northeast Pacific Program that began a series of seasonal cruises in the northern California Current in July 1997 as part of its long-term observation program (LTOP). Observations are made five times per year along the Newport hydrographic (NH) line at 44.65°N, and three times per year along a set of 4 or 5 zonal sections between 42°N and 45°N. Additional data sets presented here include hydrographic observations along CalCOFI line 67 conducted in November 2000 by the Naval Postgraduate School (NPS) and the Monterey Bay Aquarium Research Institute (MBARI), as well as tracks depicted by isobaric (400 dbar) subsurface floats deployed in November 1998 and May 1999.

LARGE-SCALE OCEANIC ATMOSPHERIC CONDITIONS

After the dramatic transition in 1998 from one of the strongest El Niño events in the century to a strong La Niña event (Hayward et al. 1999; Schwing et al., in press), 2000 and early 2001 were marked by a continuation of La Niña conditions in the tropical Pacific. As indicated by the multivariate ENSO index, or MEI (Wolter and Timlin 1998), winter 2000–2001 was the third consecutive winter in which weak to moderate La Niña conditions intensified (fig. 3). As of April 2001, the MEI had remained negative for 33 consecutive months, the longest continuous negative period since the 1976 climate regime shift. Negative MEI values historically have persisted for 20–35-month periods (cf. 1995–97 La Niña in fig. 3), suggesting that multiyear La Niña events are common (Schwing et al., in press). A number of unusual physical and biological observations

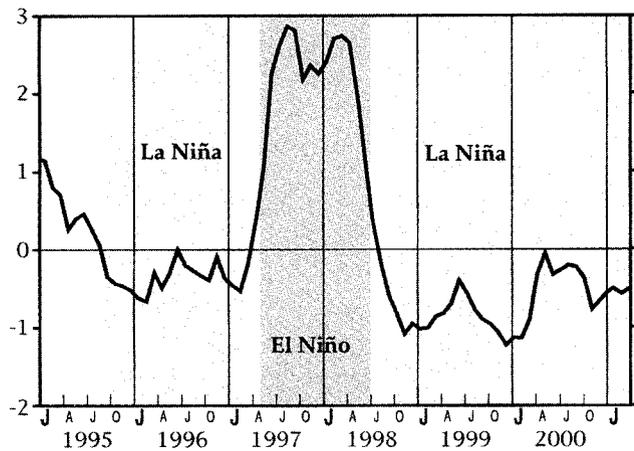


Figure 3. Monthly time series of the multivariate ENSO index, or MEI (Wolter and Timlin 1998), for January 1995–March 2001. Series highlights rapid transition from El Niño to La Niña in 1998, and extended negative phase of MEI associated with the 1998–2001 La Niña.

along the West Coast are highly suggestive of a regime shift in the north Pacific in 1998 or 1999 (Schwing and Moore 2000; Schwing et al. 2000).

Atmospheric anomalies throughout the Pacific Ocean during 2000 and early 2001 (fig. 4) continued a pattern typical of La Niña that developed in late 1998 (Hayward et al. 1999; Bograd et al. 2000; Schwing et al., in press). Generally clockwise wind anomalies in the northeast Pacific were associated with a strong, persistent North Pacific High. These contributed to unusually robust upwelling-favorable winds along much of the North American west coast. An unusually deep Aleutian Low in winter 2000–2001 was linked to anomalous cyclonic winds over the Gulf of Alaska and the persistence of a storm track well north of its typical winter path through the Pacific Northwest.

Since late 1998, a region of cooler than normal sea-surface temperatures (SSTs) has stretched roughly along

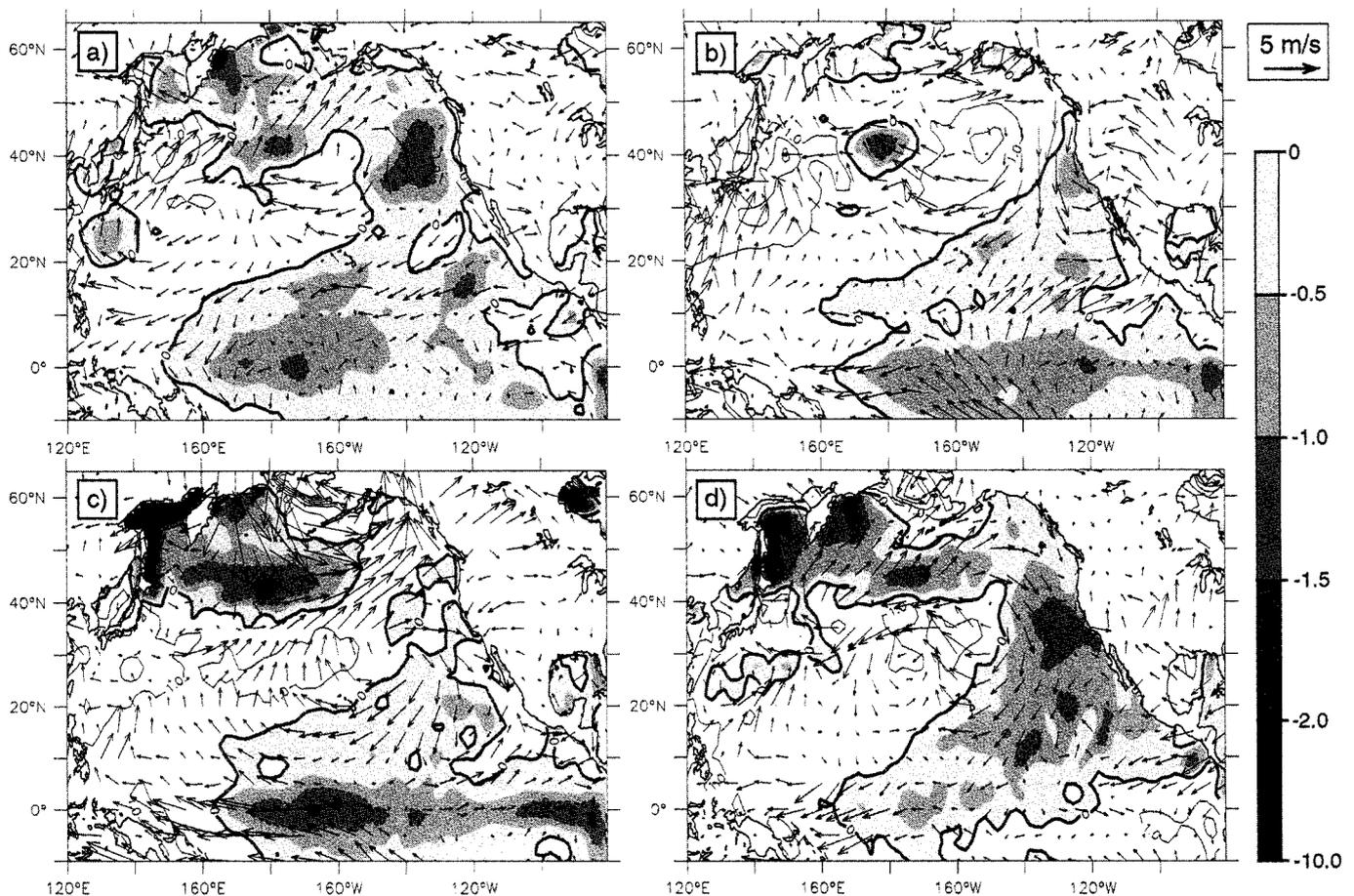


Figure 4. Anomalies of surface wind velocity and sea-surface temperature (SST) in the north Pacific Ocean: a, July 2000 wind and May–July 2000 SST; b, October 2000 wind and October–November 2000 SST; c, January 2001 wind and December 2000–January 2001 SST; and d, April 2001 wind and SST. Arrows denote magnitude and direction of wind anomaly. Contours denote SST anomaly. Contour interval is 1.0°C. Negative SST anomalies are shaded. Wind climatology period is 1968–96. SST climatology period is 1950–79. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

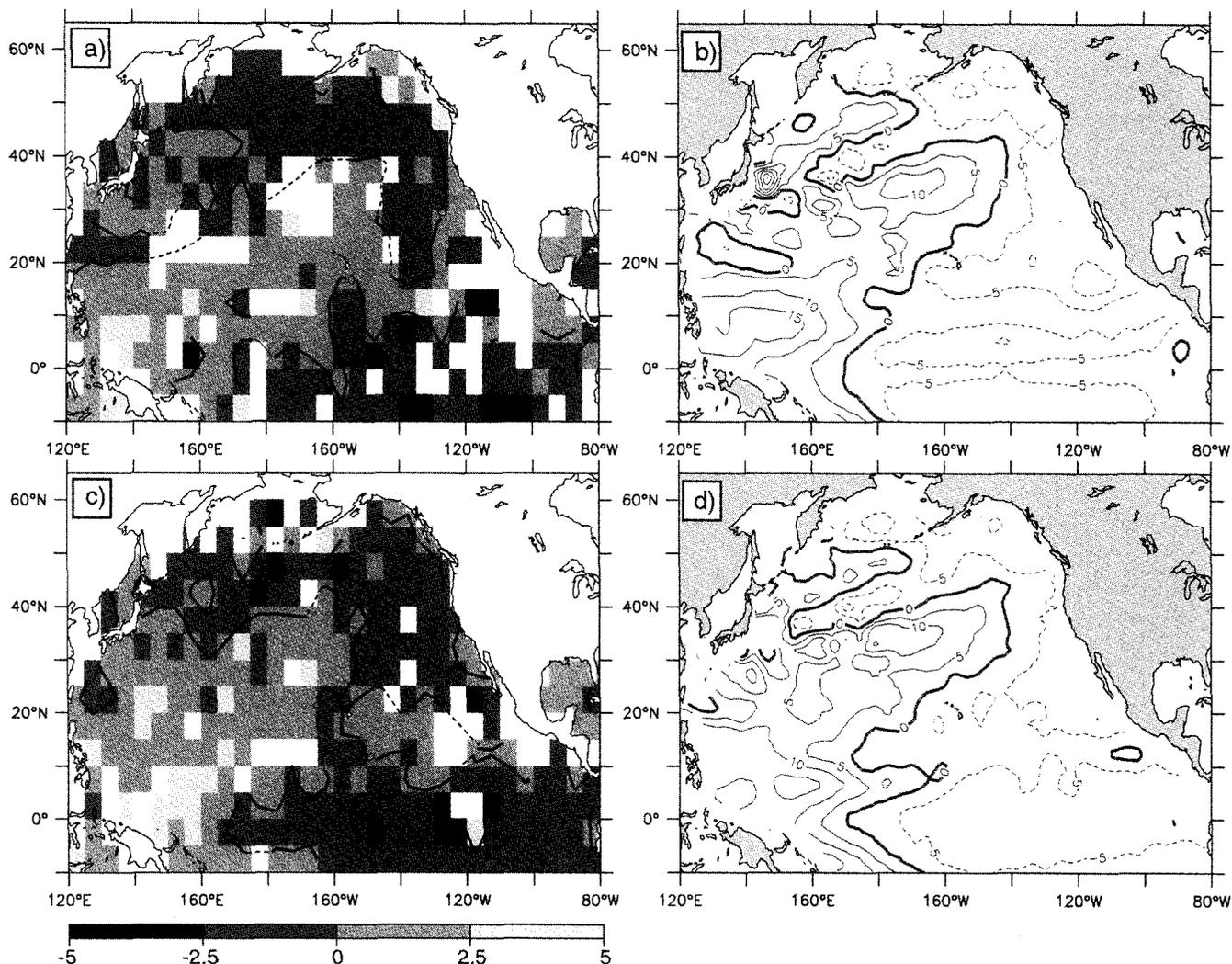


Figure 5. Seasonal subsurface anomalies in the North Pacific. Anomalies of (a) 100 m temperatures for May–July 2000; (b) sea-surface heights (SSHs) for May–June 2000; (c) 100 m temperatures for November 2000–January 2001; (d) SSHs for November 2000–January 2001. Temperature anomalies based on the Global Temperature–Salinity Profile Program database, monthly averaged on a 1° spatial grid. Anomalies were computed by subtracting the 1° monthly climatologies (base period 1945–96) of the World Ocean Database 1998 (Levitus et al. 1998) from the gridded observations. Anomalies are averaged into $5^\circ \times 5^\circ$ spatial boxes. Zero anomaly contours are shown. Lighter shades denote positive anomalies. White areas denote no data for the period shown. SSH anomalies provided by the NOAA Laboratory for Satellite Altimetry, based on data from the joint NASA/CNES TOPEX/Poseidon satellite altimeter. SSH deviations were averaged by month in 4° longitude \times 1° latitude cells. Anomalies were computed by removing the annual and semiannual harmonics from 1993 through 1995. Contour interval is 5 cm.

the axis of the North Pacific trade winds from the western equatorial Pacific to Baja California, and along the North American west coast (cf. Hayward et al. 1999; Bograd et al. 2000). Cool anomalies also were common north of 40°N , and spanned the equator east of the date line. Positive SST anomalies were maintained south of 40°N from the western North Pacific to north of Hawaii. This basic SST anomaly pattern, which is seen commonly during La Niña events (Schwing et al., in press), was evident throughout 2000 and early 2001 (fig. 4). In summer 2000 and again in spring 2001, an SST anomaly minimum developed west of the California Current system (CCS). It is thought that these anomalously cool SSTs were created and maintained by regional wind

anomalies, primarily through Ekman processes, geostrophic transport, sensible and latent heat fluxes, and vertical mixing (Schwing et al., in press).

The SST anomalies during the past year were a general reflection of the upper water column, as defined by anomalies of temperature at 100 m depth and sea-surface heights from the TOPEX/Poseidon satellite altimeter (fig. 5). Particular key features are the arc of cool anomalies along the West Coast and eastern tropical Pacific; extremely warm anomalies in the western tropical Pacific; and warm anomalies extending across the North Pacific from east Asia to north of Hawaii. These temperature and height anomaly patterns have been present since late 1998 (Schwing et al., in press), supporting the idea that

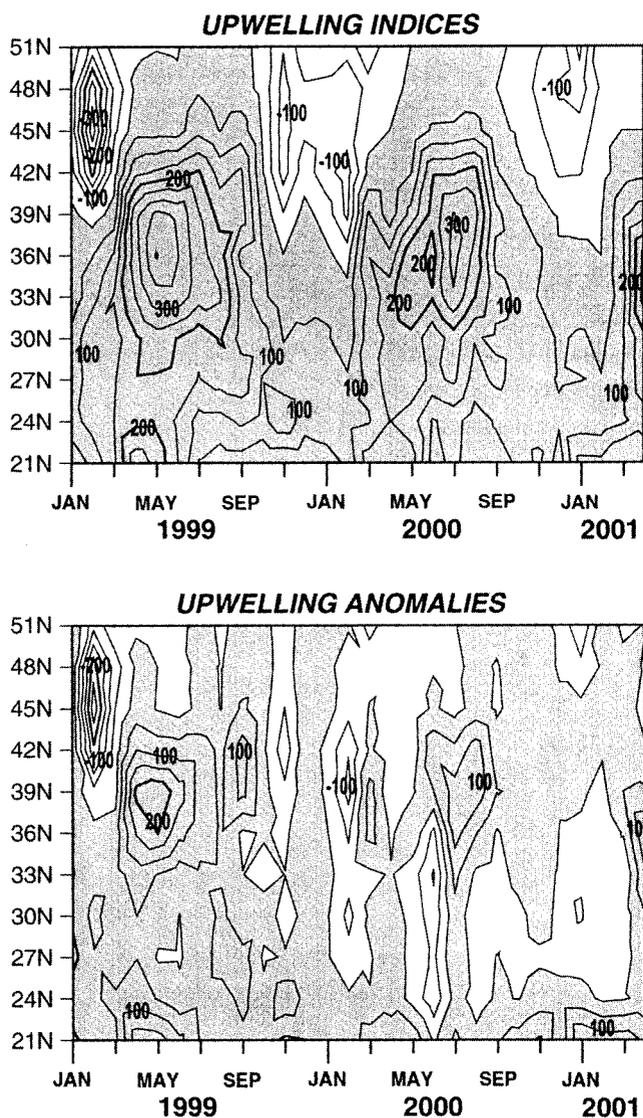


Figure 6. Monthly upwelling indices and upwelling anomalies for January 1999–April 2001. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in m^3/s per 100 km of coastline.

a regime shift occurred about that time. Although SSTs were unseasonably cool in the southern CCS, subsurface temperature anomalies were positive. This may indicate an anomalously deep thermocline, possibly due to weaker than normal upwelling (fig. 6), or it may reflect downwelling associated with coastal wave activity (Clarke and Van Gorder 1994; Meyers et al. 1998). The ocean anomalies in figures 4 and 5 indicate an excess amount of heat stored in the upper ocean in the western tropical Pacific. This is conducive to the future development of El Niño, provided the proper atmospheric conditions develop (McPhaden 1999).

At the time of this writing (May 2001), mature cold episode (La Niña) conditions continued in the tropical Pacific (NCEP 2001). Across the central and eastern

equatorial Pacific, SSTs remained 0.5° – 1.0° C below average, and the thermocline was unusually shallow. Equatorial Pacific thermocline temperatures were up to 2° – 4° C above (below) normal east (west) of 160° W. A gradual expansion of positive equatorial subsurface temperature anomalies into the central Pacific has continued for the past several months. This evolution characterizes the mature phase of La Niña events. The general impression from climate model forecasts is a continued gradual weakening of tropical Pacific La Niña conditions, with near-normal or slightly warmer than normal (weak El Niño) conditions evolving during the second half of 2001. However, the models are not in complete agreement on this; some predict that La Niña will continue into late 2001.

COASTAL CONDITIONS

Monthly coastal upwelling indices (Bakun 1973; Schwing et al. 1996) indicate generally stronger than normal upwelling in the CCS since the onset of La Niña in late 1998 (fig. 6). Following record upwelling anomalies off central California during the 1999 upwelling season (Schwing et al. 2000), upwelling was again unusually strong during the 2000 season from Point Conception to the Columbia River and off southern Baja California. Negative anomalies (weaker than normal upwelling) prevailed through 2000 and early 2001 off northern Baja California and southern California. Anomalously strong downwelling off the Pacific Northwest characterized the past three winters. In April 2001, stronger than normal upwelling extended throughout the CCS.

Winds measured by NDBC coastal buoys in the CCS (fig. 7) display the short-term variability associated with synoptic atmospheric events, superimposed on the annual climatological cycle of strong southward winds in summer and northward or weak southward winds in winter. Wind vectors align strongly with the local coastline (table 1). Coastal winds during 2000 displayed the typical pattern of stronger magnitudes and higher synoptic to annual variability off northern California, and weaker and less variable winds within the Southern California Bight (fig. 7). Alongshore winds were near their long-term norm, punctuated by a number of stronger than normal southward (more upwelling-favorable) wind events during the upwelling season, and occasional relaxation episodes of downwelling or weak upwelling.

Coastal SSTs cooled (warmed) in response to local upwelling (downwelling) wind events, particularly in the northern CCS (fig. 8). Strong downwelling episodes occurred in November 1999 and January–February 2000 over most of the CCS. Although these winds resulted in some ocean warming, SSTs remained near or below their seasonal norms. Significant upwelling events were noted off northern California and Oregon in late March,

Alongshore Winds 1999 to 2000

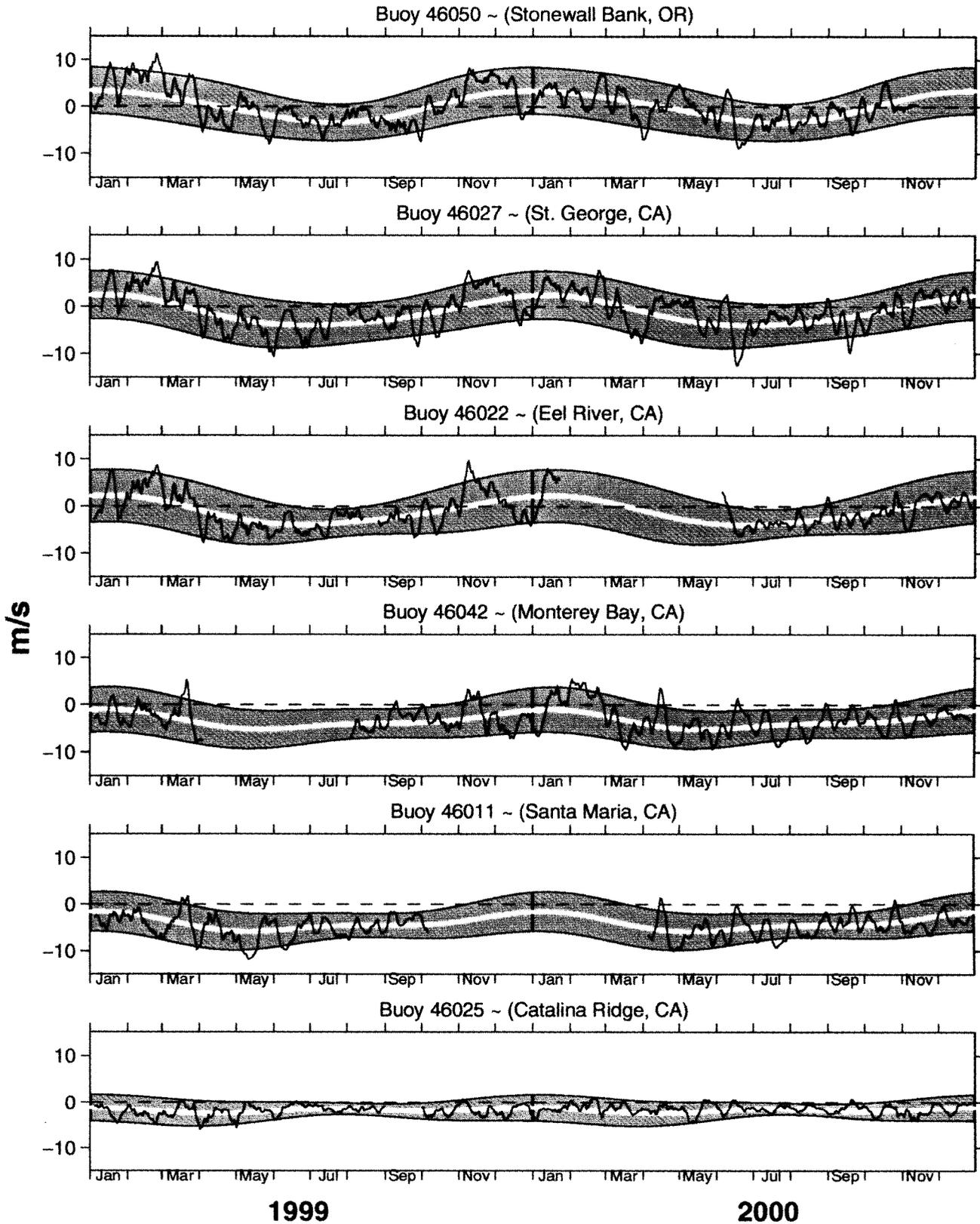


Figure 7. Time series of daily-averaged alongshore winds for January 1999–December 2000 at selected NDBC coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard error for each Julian day. Series have been smoothed with a 7-day running mean. The periods used for calculating the climatology at each site and the alongshore angle are shown in table 1.

Sea Surface Temperatures 1999 and 2000

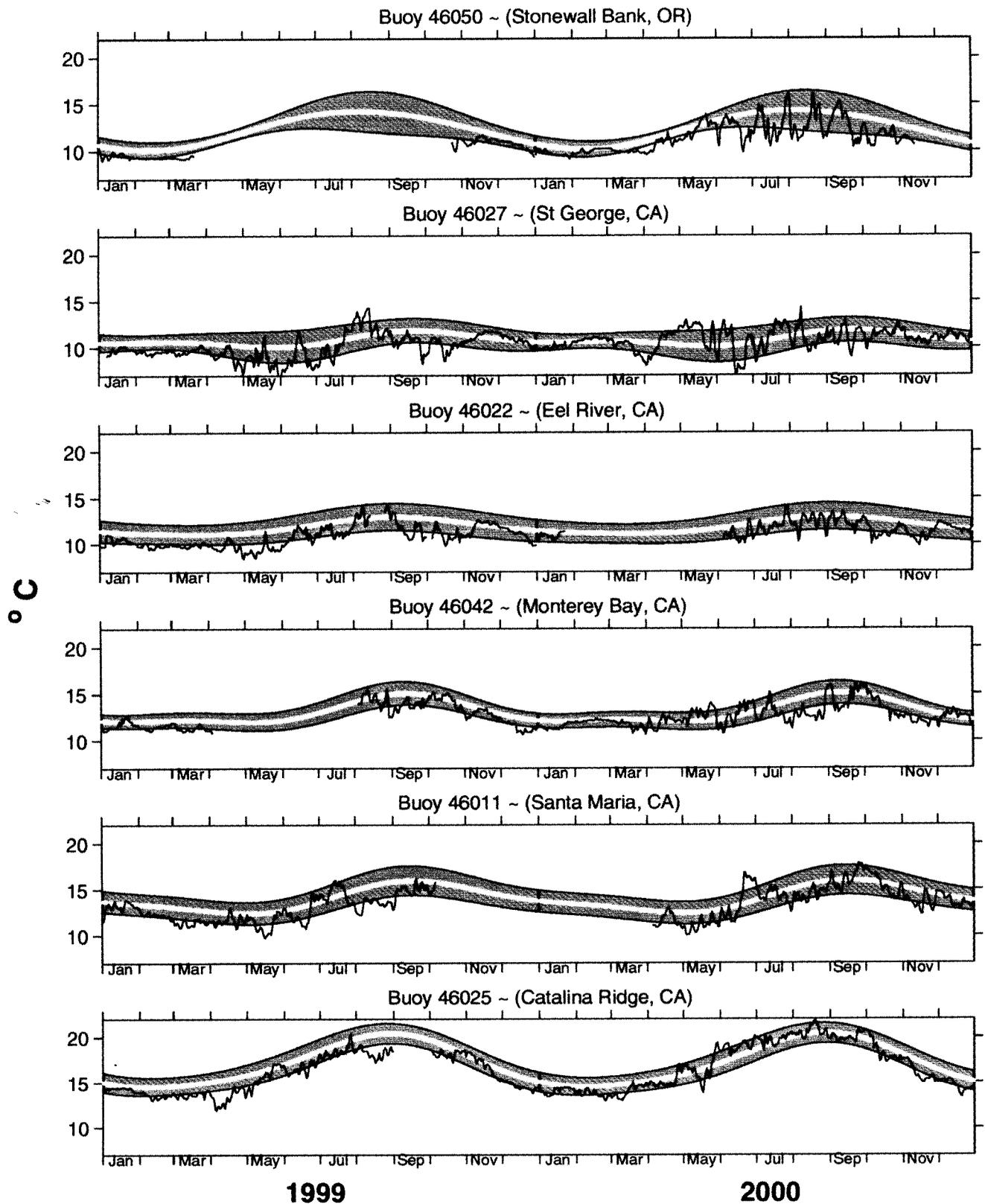


Figure 8. Time series of daily-averaged SST for January 1999–December 2000 at selected NDBC coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard error for each Julian day. The periods used for calculating the climatology at each site are shown in table 1.

June, and September 2000. Farther south, strong upwelling events occurred in May, August, and November 2000. The multiyear trend of below normal temperatures continued in the northern CCS, although the anomalies were not as extreme as in 1999. SSTs were near-seasonal off southern California through most of the previous year.

IMECOCAL SURVEY CRUISES

Data gathered during observations since last year's report are described below. Please refer to the IMECOCAL Web page (<http://imecocal.cicese.mx>) for more information about the program, 1997–2001 databases, and future cruise schedules.

0004 (4–24 April 2000). Equatorward flow parallel to the coast was the main characteristic during this cruise, as depicted by the near-surface geostrophic currents (fig. 9). The salinity minimum indicates that the core of the California Current lies approximately 200 km from the coast except off Punta Eugenia, where it veers around a small cyclonic eddy centered on station 117.55. Offshore, the flow follows two anticyclonic meanders, one east of Isla Guadalupe and the other centered on station 127.60. Both meanders are associated with warm and higher-salinity waters. Inshore, two upwelling regions, characterized by their low sea-surface temperatures near the coast, are noticeable, one off Ensenada related to a small cyclonic eddy on station 103.35 and the other south of Punta Eugenia. Except for the poleward flow around this cyclonic eddy, no Inshore Countercurrent is noticeable during the period of this cruise. Large values of chlorophyll *a* correspond to these upwelling regions, with concentrations above 1 mg/m^3 associated with temperatures below 15.5°C . In general, chlorophyll *a* concentrations were lower than those observed in 1999 (Bograd et al. 2000). However, March 2000 near-surface chlorophyll *a* estimates from SeaWiFS images reveal values comparable to those of April 1999 but greater than in April 2000. Temperatures on both upwelling regions were $\sim 1^\circ\text{C}$ lower than the climatological mean for the period 1950–78 (Lynn et al. 1982), while salinities were within the norm.

0007 (10–31 July 2000). A very energetic, meandering, California Current as well as coastal upwelling along northern Baja California were the typical conditions during this cruise (fig. 10). The California Current enters the survey region as an eastward flow, around stations 103.60 and 107.60, moves east and reaches the coast near Punta Baja, where it turns sharply to later follow an equatorward path around Punta Eugenia. At the southern limit of the survey region, it splits into two branches, one offshore that entrains warmer, more saline water from the west to finally flow south, and the other moving onshore to finally impinge on the coast south

of Punta Eugenia. Inshore of the California Current core, poleward flows are associated with a cyclonic-anticyclonic eddy pair between lines 100 and 107. The cyclonic eddy entrains some California Current water, which is driven northward by the anticyclonic eddy to form the Inshore Countercurrent for the southern California region. North of 27°N , temperatures were minimal near the coast south of the coastal prominences Punta Banda (Ensenada), Punta Baja, and Punta Eugenia. High temperature (18.5°C) inside Bahía Vizcaino indicates that the summer-autumn anticyclonic eddy is well developed (Amador-Buenrostro et al. 1995). Large spatial gradients of up to $6^\circ\text{C}/100 \text{ km}$ between the inshore and offshore waters are discernible. The triangular coastal region of large spatial temperature gradients between Punta Baja and Punta Eugenia is also an area of high concentrations of chlorophyll *a*. Except for this region where 10 m temperatures were $\sim 1^\circ\text{--}2^\circ$ below the climatological mean (Lynn et al. 1982), water temperatures were normal north of 28°N and warmer than normal south of this latitude.

0010 (10–31 October 2000). Near-surface geostrophic currents indicate that the California Current enters the survey area from the north and flows close to shore, as indicated by the lower salinities near the coast (fig. 11). A portion of the current moves farther offshore and back north as part of an anticyclonic meander to later return around the cyclonic eddy east of Isla Guadalupe. For this cruise, there was no clear indication for the presence of a poleward inshore countercurrent. Both 10 m temperature and salinities were close to normal (Lynn et al. 1982). Chlorophyll *a* concentrations larger than 1 mg/m^3 were observed only near shore on the northernmost portion of the survey region (stn. 100.30), while the rest of the surrounding area had low concentrations, in general associated with warmer ($>19^\circ\text{C}$) and saltier ($33.7 < S < 34.3$) waters.

0101 (16 January–5 February 2001). During this cruise, near-surface currents depict a slow-moving and broad California Current, with weak onshore-offshore dynamic topography gradients (fig. 12). The same weak gradients were reflected in the other measurements. Chlorophyll *a* concentrations larger than 1 mg/m^3 were associated with the surroundings of Punta Eugenia as well as with a small upwelling region around station 103.30. Chlorophyll *a* concentrations during this cruise were larger than those reported for winter 2000 (Bograd et al. 2000). Throughout most of the region, 10 m temperature and salinity were normal.

CALCOFI SURVEY CRUISES

We summarize a portion of the data obtained on each of the quarterly CalCOFI cruises conducted since the preparation of last year's report, focusing on near-surface

IMECOCAL CRUISE 0004

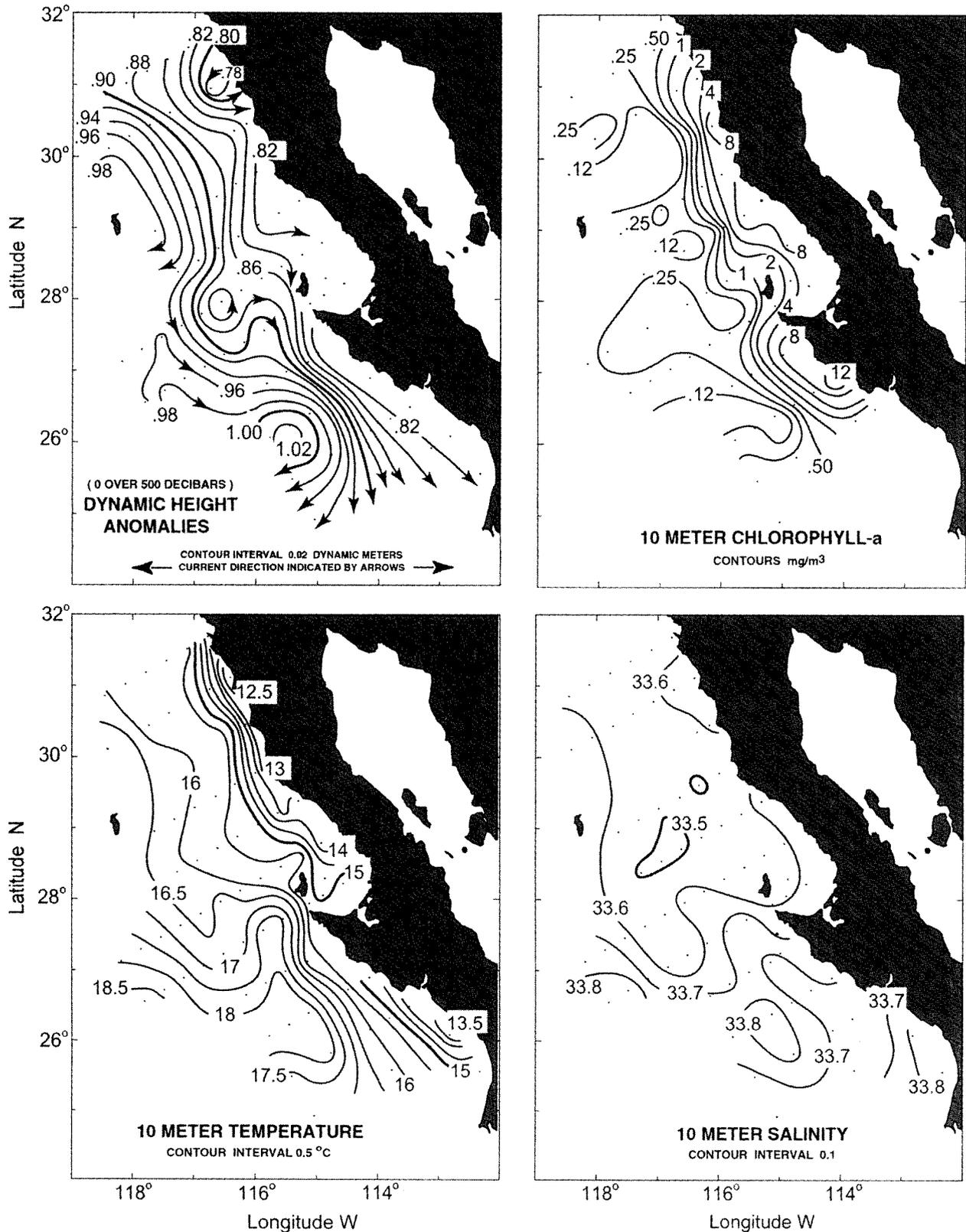


Figure 9. Spatial patterns for IMECOCAL cruise 0004 (4–24 April 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll a, 10 m temperature, and 10 m salinity.

IMECOCAL CRUISE 0007

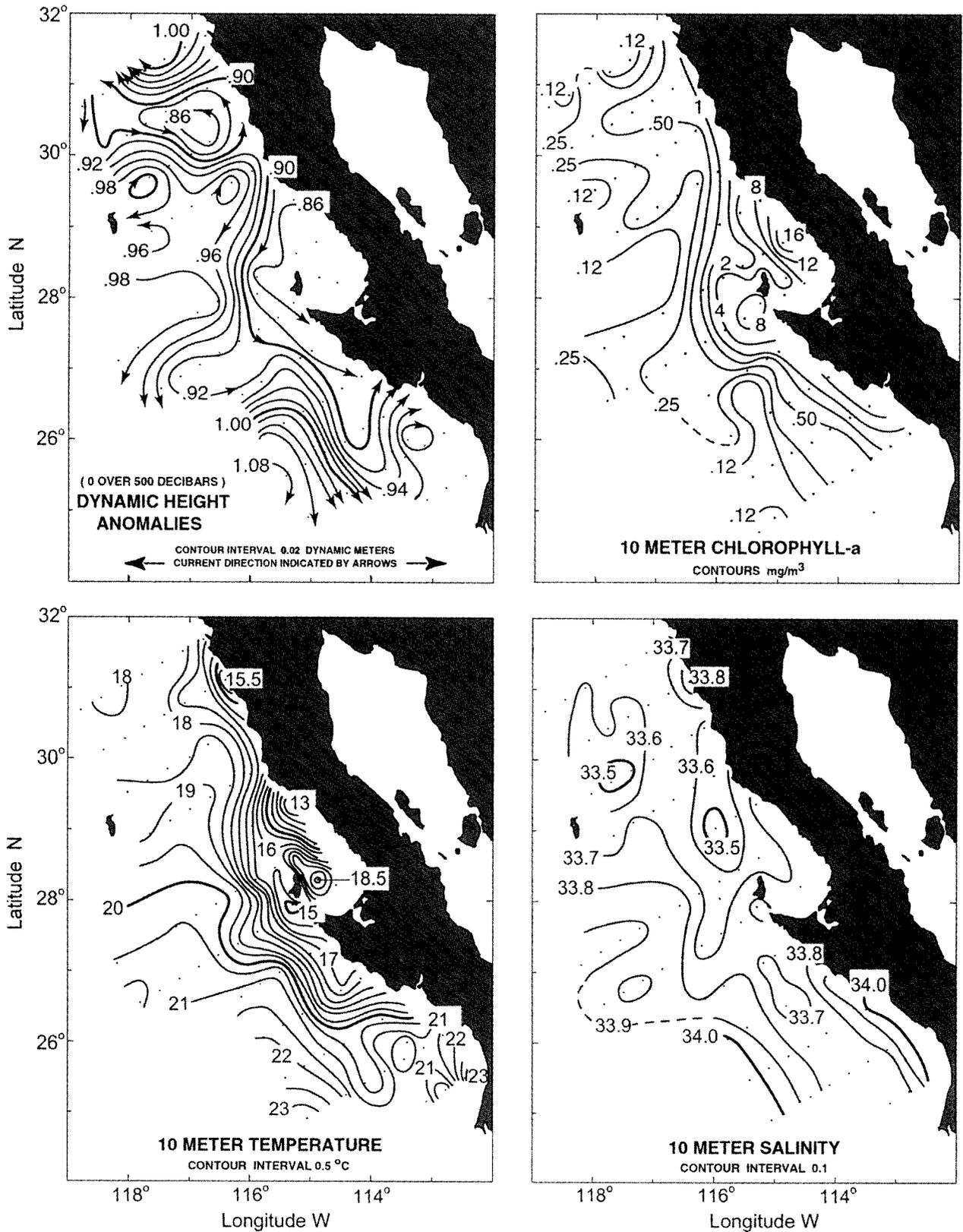


Figure 10. Spatial patterns for IMECOCAL cruise 0007 (10-31 July 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll a, 10 m temperature, and 10 m salinity.

IMECOCAL CRUISE 0010

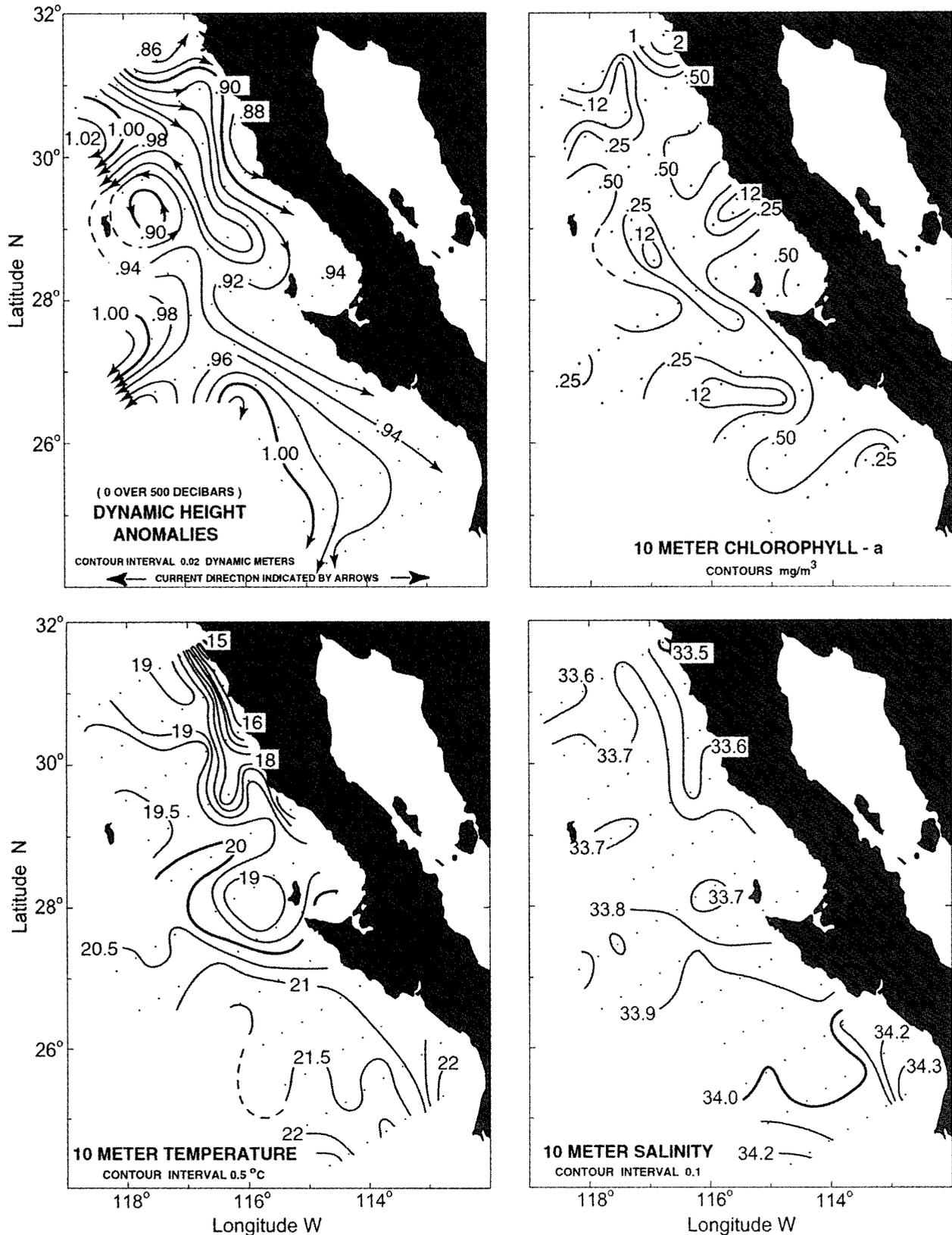


Figure 11. Spatial patterns for IMECOCAL cruise 0010 (10–31 October 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll a, 10 m temperature, and 10 m salinity.

IMECOCAL CRUISE 0101

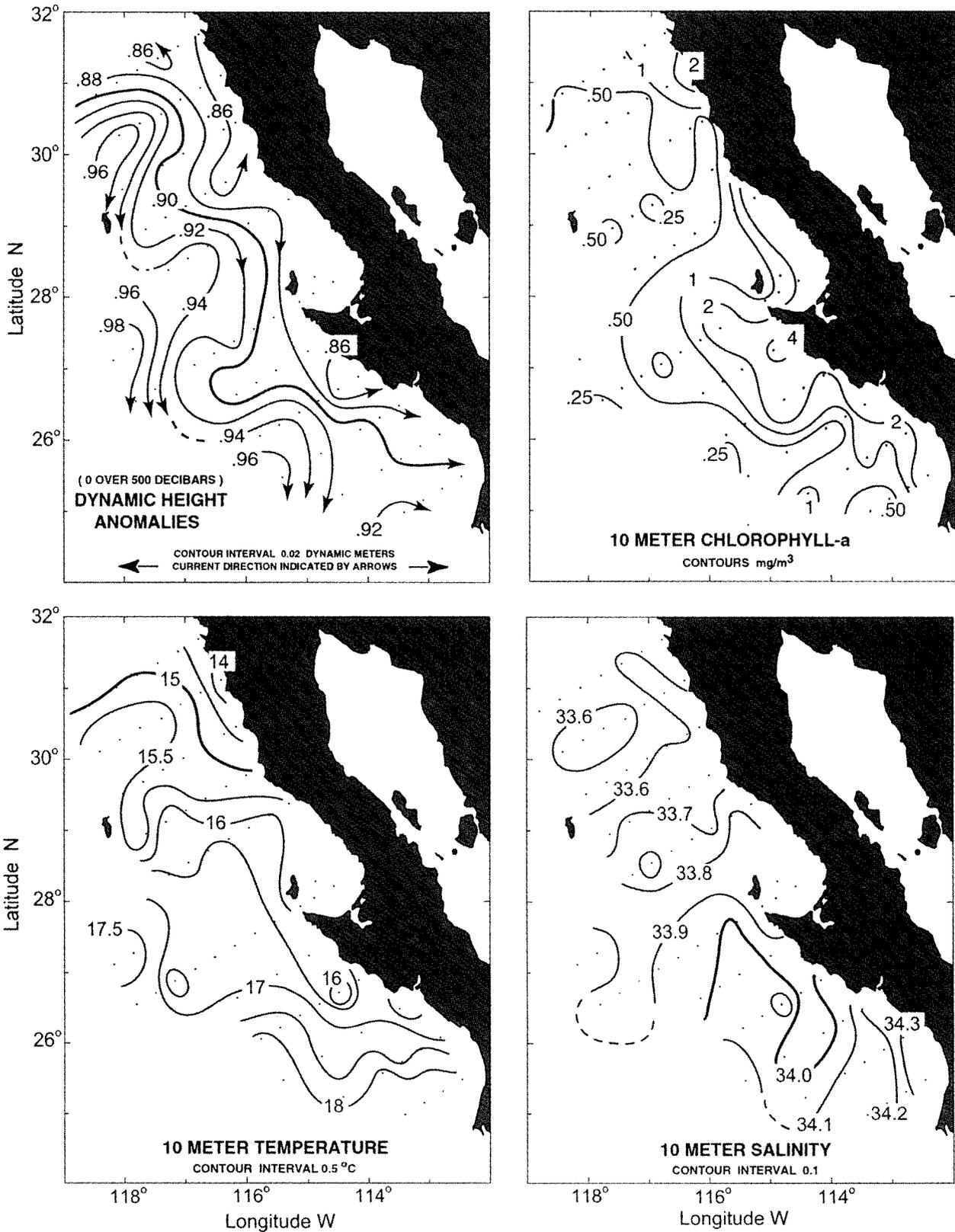


Figure 12. Spatial patterns for IMECOCAL cruise 0101 (16 January–5 February 2001), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll a, 10 m temperature, and 10 m salinity.

CALCOFI CRUISE 0004

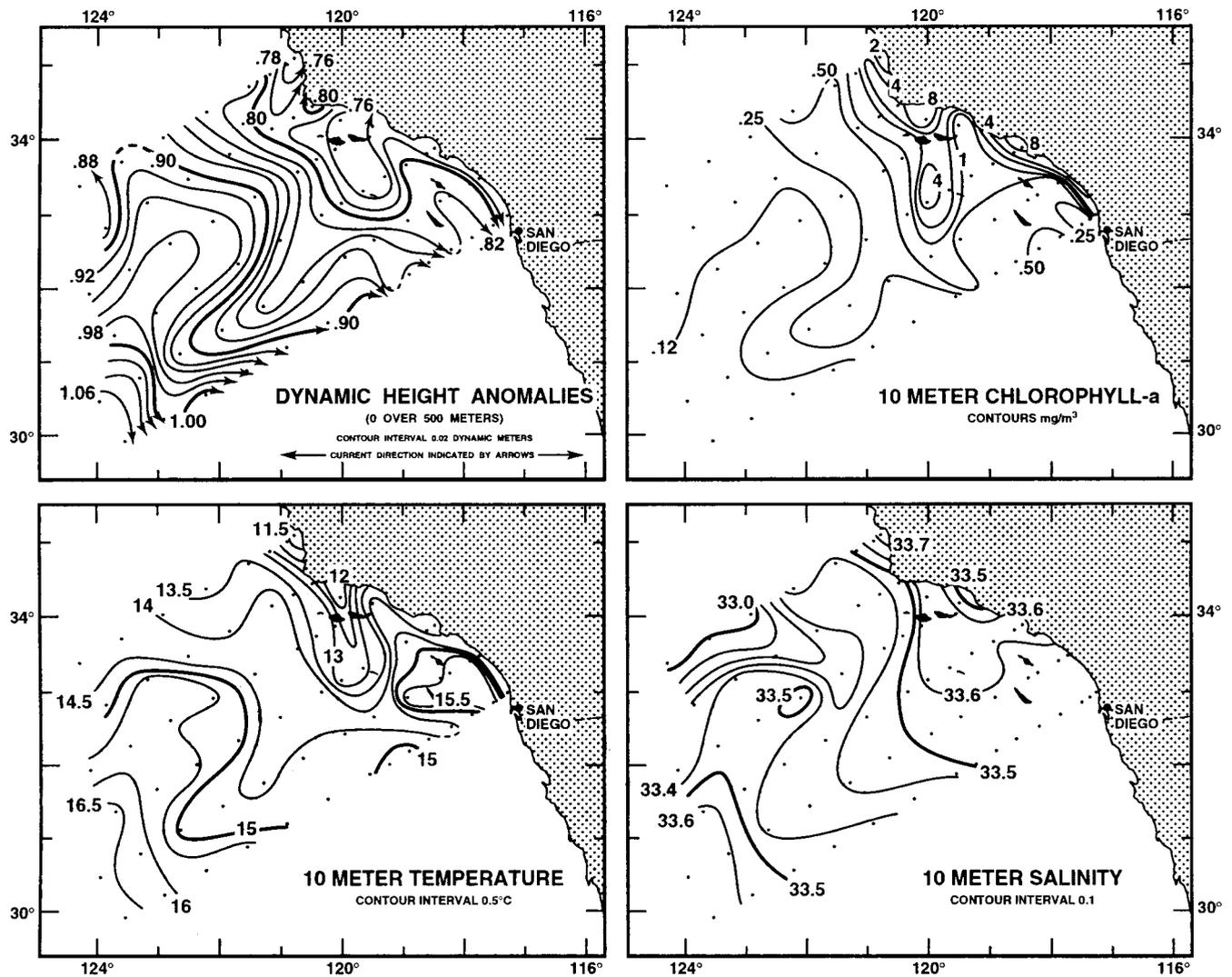


Figure 13. Spatial patterns for CalCOFI cruise 0004 (7–29 April 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

physical and biological fields. The reader is encouraged to refer to the cruise data reports (e.g., Scripps Institution of Oceanography 2000) or the CalCOFI Web page (<http://www.calcofi.org>) for a complete presentation of the data sets, as well as for updates on subsequent cruises. A CD-ROM containing the first 50 years of CalCOFI data (1949–99), as well as software tools for navigating and extracting data segments, is also available.

0004 (7–29 April 2000). Preliminary data from this cruise were included in last year's report (Bograd et al. 2000). As has been the case for the past several springs, this cruise surveyed farther north than usual, along lines 73, 70, and 67, performing underway measurements including the tracking of sardine and anchovy eggs with the CUFES (see the Biological Patterns section below). The 0/500 dbar dynamic height field reveals a strong

California Current, which enters the region near stations 77.70–90 and meanders sharply between lines 87 and 93 (fig. 13). The zonal flow evident offshore may indicate the early stages of large eddy development. This region was characterized by relatively warm and saline near-surface waters. The inshore region consisted of two dynamic regimes: (1) an area of cool, saline, near-surface waters extending southward along the coast and offshore from Point Conception, which results from the lifting (upwelling) and offshore advection of deeper waters, and (2) a pool of warm water, apparently of southerly origin, encompassing the southeastern portion of the Southern California Bight. However, there was no evidence of significant poleward flow (the Inshore Countercurrent) during the period of this cruise. Chlorophyll *a* values were high within a narrow strip along the coast, and

CALCOFI CRUISE 0007

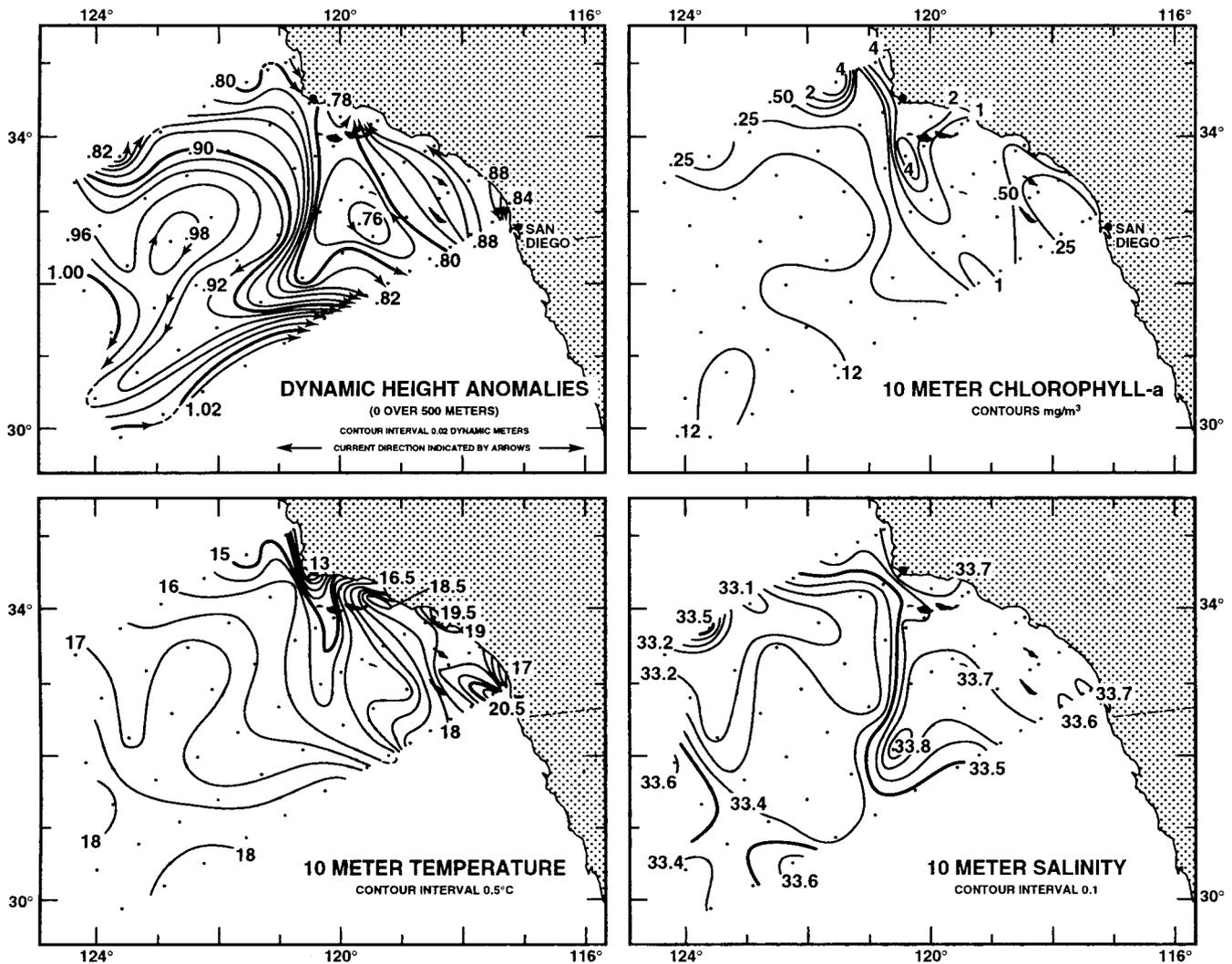


Figure 14. Spatial patterns for CalCOFI cruise 0007 (29 June–14 July 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

within the tongue of cool water extending south from Point Conception, but overall chlorophyll values were much lower than those observed the previous April (Bograd et al. 2000).

0007 (29 June–14 July 2000). The near-surface circulation pattern in July 2000 was similar to that seen in April, although we do not know whether this constituted a stable pattern over the intervening period (fig. 14). The California Current was vigorous, and again had a pronounced meander along lines 90 and 93. The 0/500 dbar dynamic height field reveals a closed circulation (anticyclonic eddy), characterized by relatively warm and saline waters, in roughly the same location as the large California Current meander seen in April (line 83). Again, we cannot infer the stability of this feature from the hydrographic cruises alone. The poleward Inshore

Countercurrent had developed by this time, filling the near-surface Southern California Bight with warm and saline waters. Another closed circulation feature (a cyclonic eddy) is evident just west of the submerged gappy ridge that extends south from Santa Rosa Island (34.0°N, 120.1°W). The inshore area of cool temperatures and high chlorophyll *a* content was confined to the coast near Point Conception, and within the tongue that again extends southward just west of the ridge. Overall chlorophyll values were fairly typical for a midsummer cruise. **0010 (12–31 October 2000).** The near-surface circulation in October 2000 was considerably more energetic than in a typical autumn cruise (fig. 15; e.g., see the mean seasonal circulation patterns in Bograd et al. 2000, fig. 10). The California Current entered the region at stations 77.90–100, and then meandered through the

CALCOFI CRUISE 0010

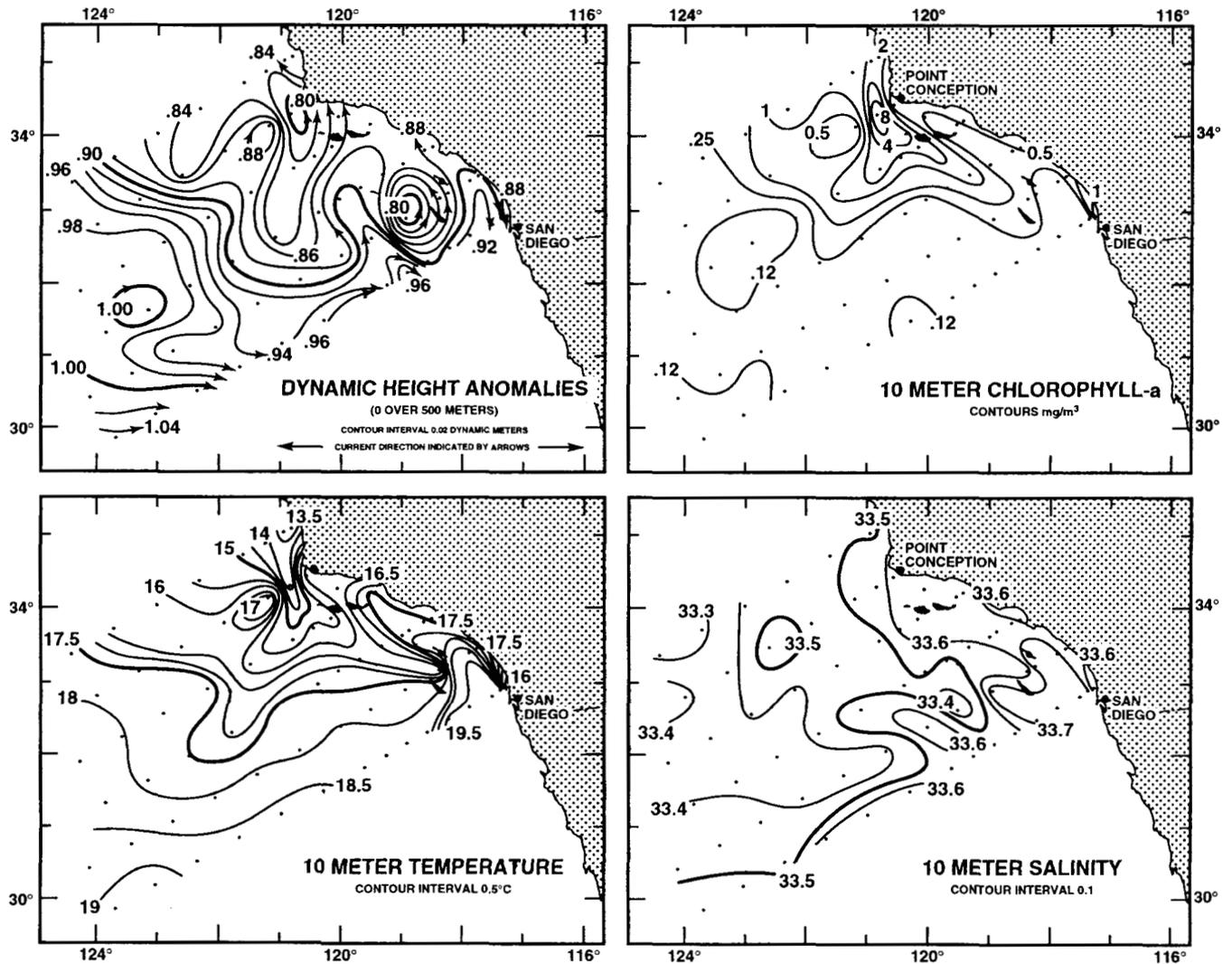


Figure 15. Spatial patterns for CalCOFI cruise 0010 (12–31 October 2000), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll a, 10 m temperature, and 10 m salinity.

center of the grid and into the Southern California Bight. A vigorous cyclonic eddy, composed of cool, fresh water, was situated near the center of the bight. This feature shows up as a large SST anomaly (-3°C) in the line 90 temperature time series (fig. 18 below). The near-coastal poleward flow, which is often well developed at this time of the year, was confined to the southeastern portion of the bight, where 10 m temperatures approached 20°C . The upwelling regime surrounding Point Conception, which is characterized by cool, salty, high-chlorophyll near-surface waters, is again clearly evident. Chlorophyll values were fairly high for an October cruise.

0101 (7–26 January 2001). The near-surface circulation pattern during January 2001 (fig. 16) was again quite energetic on the offshore side of the grid, but quiescent inshore of station 70. The core of the California Current,

as revealed by the circulation patterns and the 10 m salinity fields, was well offshore, and appeared to meander around a large anticyclonic eddy, centered near station 90.100, which had a pronounced near-surface temperature (warm) and salinity (salty) signature. Large eddies have often been observed on this portion of the grid. All features had weak horizontal gradients near shore, including the region around the Point Conception upwelling center. Chlorophyll values, highest near Point Conception and in the Santa Barbara Basin as always, were modest over most of the grid.

In 2000, NPS and MBARI occupied CalCOFI line 67 five times. Measurements from the September 2000 transect are shown in figure 17. The California Current

CALCOFI CRUISE 0101

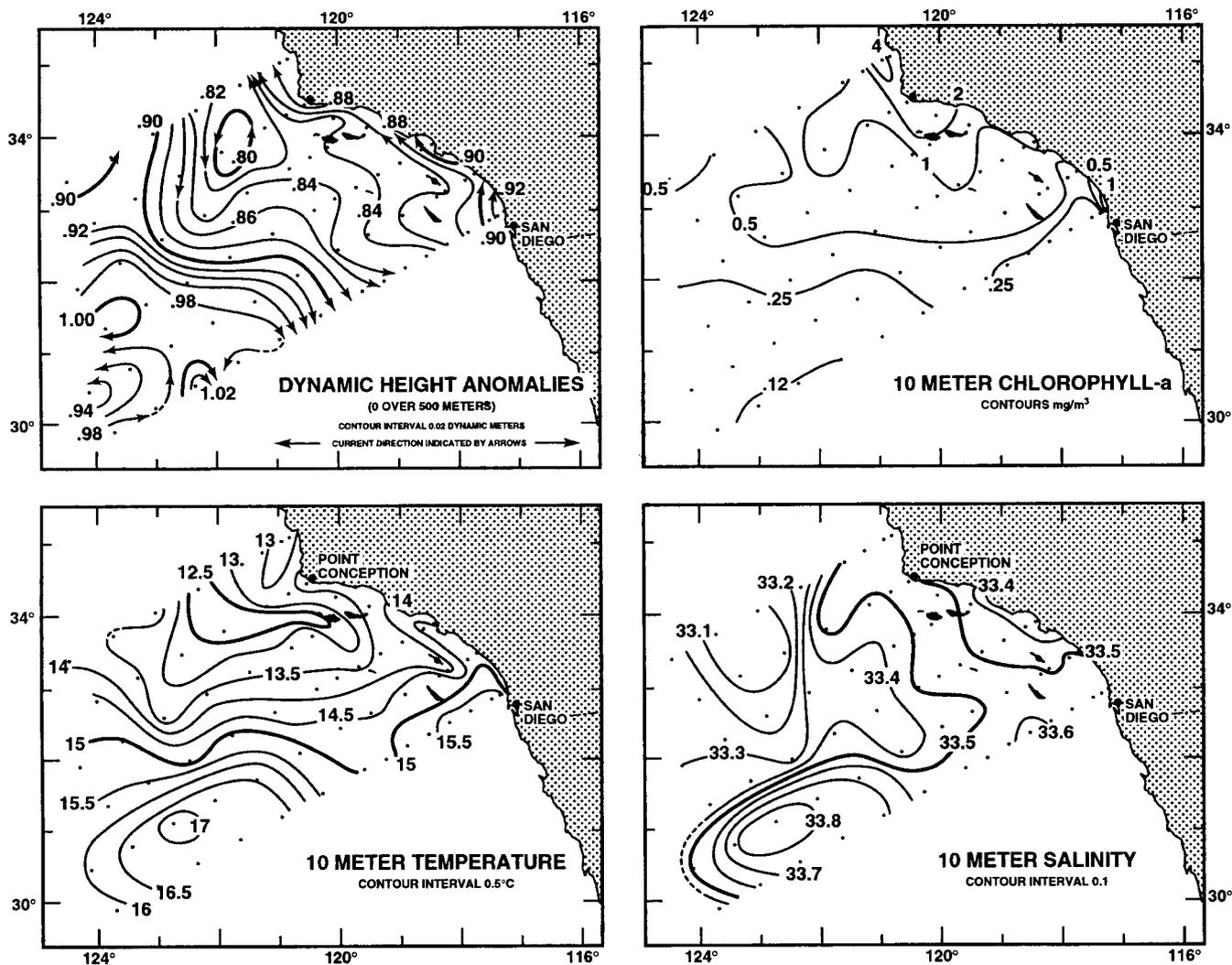


Figure 16. Spatial patterns for CalCOFI cruise 0101 (7–26 January 2001), including upper ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m chlorophyll *a*, 10 m temperature, and 10 m salinity.

is clearly evident between 150 and 350 km from shore. This region is marked by isotherms that shoal toward the coast as well as by equatorward geostrophic flow. In the upper 100 m, the core of the California Current is marked by $S < 33.4$, geostrophic velocity < -10 cm/s, and a deepening of the nutricline and oxycline from 40 dbar inshore to 80 dbar. There is a subsurface oxygen maximum at the depth of the nutricline at the offshore edge of the California Current. This shallow oxygen maximum was probably formed by photosynthetic oxygen production trapped by the strong stratification in the upper 50 dbar of the water column. Poleward geostrophic flow occurred inshore between 75 and 150 km from shore as well as west of 350 km from shore. Below 170 dbar, the spiciness of the poleward-moving water was similar, > 0.1 kg/m³, but oxygen and nitrate

levels were higher in the offshore poleward flow. For the offshore poleward flow, the water mass characteristics near the surface were similar to those observed in the equatorward flow immediately to the east; this may indicate the presence of an eddy at this location.

The time series of 10 m temperature anomalies along line 90 displays the sequence of strong interannual changes experienced over the last four years (fig. 18). This updated figure from last year's report (Bograd et al. 2000) covers the period from 1997 through January 2001. The first half of the series is dominated initially by near-surface warming, then cooling, both associated with the strong 1997–98 El Niño–La Niña cycle (Bograd and Lynn 2001; Lynn and Bograd, in press). After spring 1999, near-surface temperatures in the southern CCS were near their climatological means for much of the

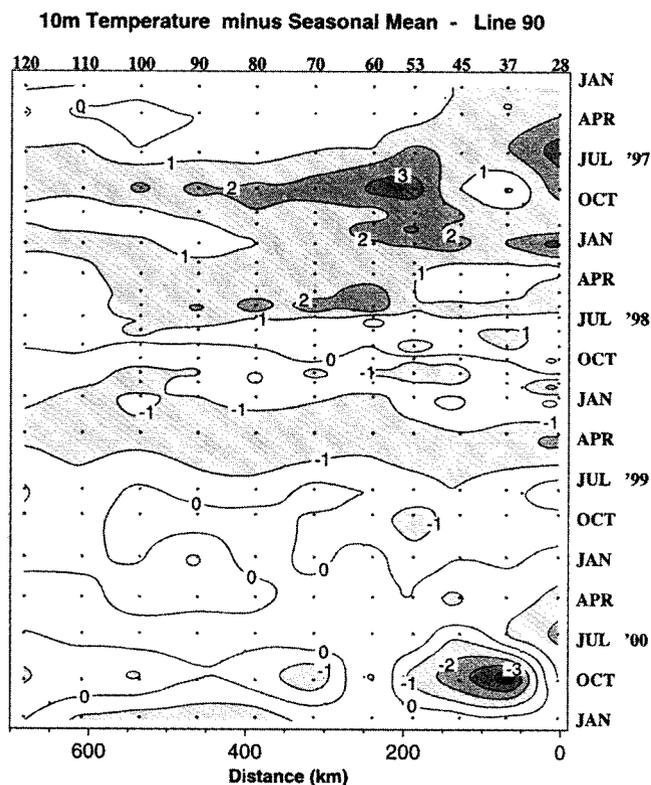


Figure 18. Ten-meter temperature anomalies for January 1997 through January 2001 for line 90 stations. Anomalies are based on the 1950–98 harmonic means.

suggest a broad coherence in forcing near-surface ocean conditions in the eastern North Pacific.

An example of composite pictures of concurrent measurements is presented in figure 20. We have constructed combined images of the geostrophic circulation using figures 9–12 from the IMECOCAL program and figures 13–16 from the CalCOFI program, allowing a better visualization of the surface flows within the sampling domain. We can discern that the open meander on the northeastern portion of the IMECOCAL region during the July 2000 cruise (fig. 10) is an anticyclonic eddy bound to the SCB eddy. We also see that the Inshore Countercurrent, described above for the southeastern portion of the CalCOFI survey area (fig. 14), is in reality the continuation of the Southern California Bight cyclonic eddy typical of this season. Similar interpretations may be deduced from the other frames that show how combining concurrent observations from separate programs expands our spatial coverage of the CCS and provides a clearer view of the meandering California Current.

GLOBEC LTOP CRUISES

The U.S. GLOBEC Northeast Pacific Program began a series of seasonal cruises in the northern California Current in July 1997 as part of its long-term observation program (LTOP). Observations are made five times

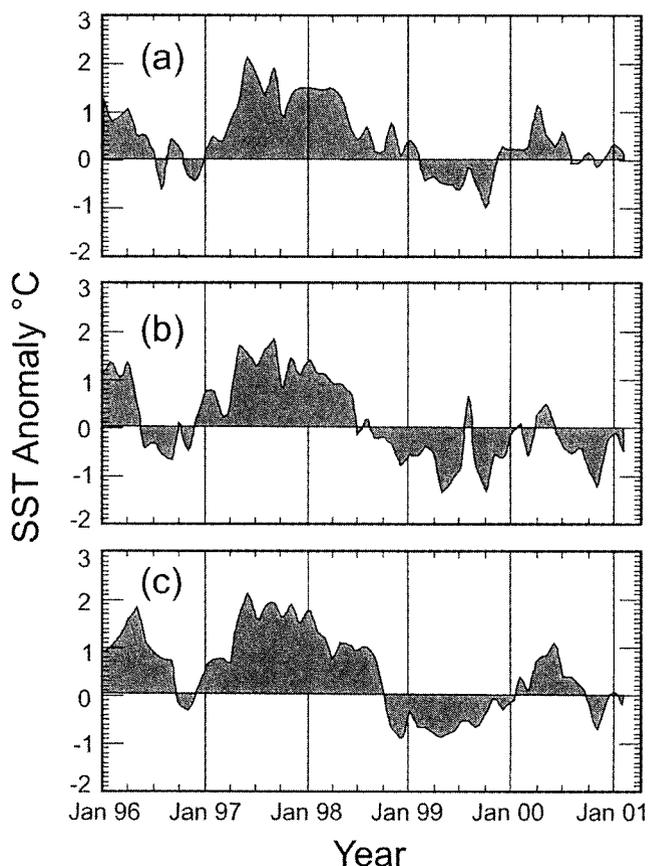
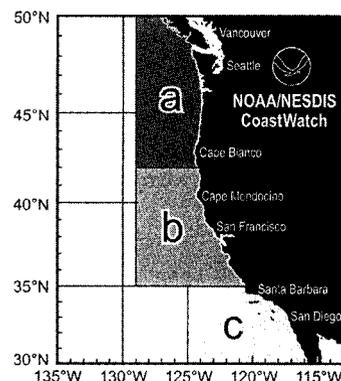


Figure 19. Regional mean SST anomalies for (a) the Pacific Northwest, (b) central coast, and (c) southern California. Figure has been redrawn from El Niño Watch page of West Coast CoastWatch Web site: <http://cwatchwc.ucsd.edu>. SST data are supplied by NOAA's National Center for Environmental Prediction.

per year along the Newport hydrographic (NH) line at 44.65°N, and three times per year along a set of 4 or 5 zonal sections between 42°N and 45°N. The NH line was occupied regularly from 1961 to 1971; Smith et al. (in press) have calculated long-term averages using data from this earlier decade for winter (1 Jan. to 29 Feb.), summer (22 June to 31 Aug.), and fall (1 Nov. to 21 Dec.), and for each month in spring, late summer, and early fall.

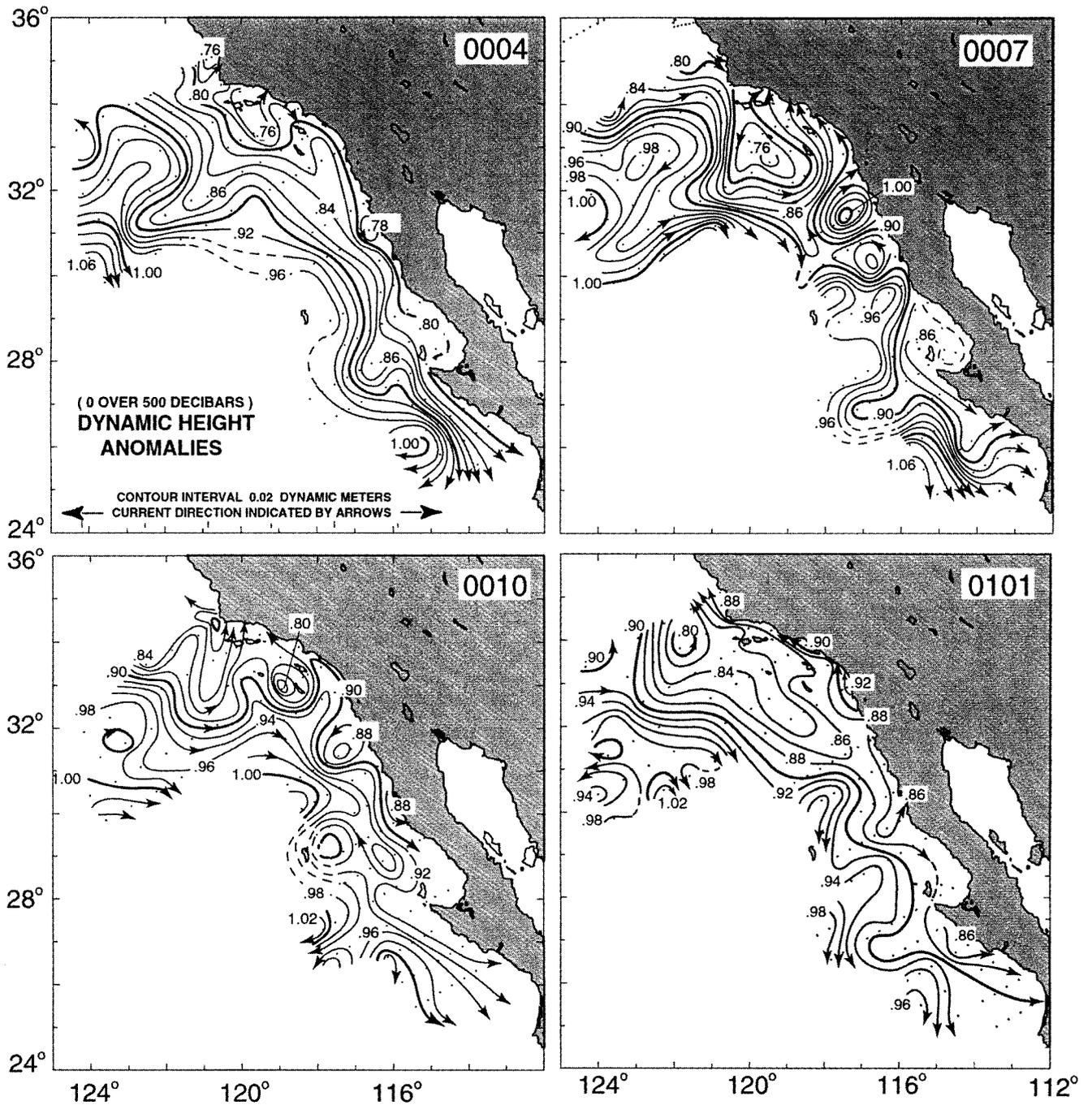


Figure 20. Spatial patterns of the ocean geostrophic flow estimated from the 0/500 dbar dynamic height fields for CalCOFI and IMECOAL cruises during 2000–2001.

Dates for the 2000–2001 GLOBEC LTOP cruises are shown in table 2. Previous observations had shown the impact of the 1997–98 El Niño in this portion of the California Current, peaking in midwinter 1997–98 and receding by the following winter (Huyer et al., in press). By late 1999, temperatures along the NH line were slightly colder and steric heights were lower than for the corresponding 1961–71 seasonal average values (Smith et al. 2001). During 2000 and early 2001, steric heights

of the sea surface along the NH line were generally within 1 standard deviation of 1961–71 seasonal average values (fig. 21). The only exception occurred in April 2000, when the inshore steric height was lower than normal, presumably because winds had been more strongly favorable for upwelling than normal during the preceding three weeks.

Temperature distributions along the NH line (fig. 22a) show the typical seasonal cycle: deep mixed layers with

TABLE 2
**GLOBEC LTOP Cruises in the
 Northern California Current, 2000–2001**

Cruise name	Dates	Sections (latitude)
W0002A	1–2 Feb. 2000	NH (44.65°N)
W0004B	11–17 Apr. 2000	NH (44.65°N), HH (44.0) FM(43.2), RR (42.5), CR (41.9)
W0007A	7–13 July 2000	NH (44.65°N), HH (44.0) FM(43.2), RR (42.5), CR (41.9)
W0009A	7–12 Sept. 2000	NH (44.65°N), HH (44.0) FM(43.2), RR (42.5), CR (41.9)
W0101B	27–19 Jan. 2001	NH (44.65°N)

weak horizontal gradients in winter, and very strong stratification in the upper 50 m in summer, with temperature decreasing toward shore over the shelf. The April 2000 section is typical for the beginning of the upwelling season (e.g., see fig. 15 of Huyer 1983): a strong onshore density gradient across the shelf is restricted to the lower half of the water column, while surface waters are still uniformly cool. The distributions of normalized temperature anomaly for 2000–2001 (calculated by subtracting the 1961–71 seasonal or monthly average and dividing this difference by the corresponding standard deviation) shows that temperatures at most depths and most stations were not significantly different from the 1961–71 epoch: values of >2 (corresponding to 95% significance) are observed in relatively small regions (fig. 22b). The surface layer values of >3 in April 2000 probably result from the unseasonably sunny weather preceding this cruise. Only a few small areas are more than 1 standard deviation colder than the 1961–71 seasonal averages. This is consistent with what we know of the Pacific decadal oscillation (PDO; Mantua et al. 1997): although we are currently in a negative phase of PDO, recent PDO values are not as low as those prevailing during the 1961–71 decade.

The regional surveys in April, July, and September 2000 show that the horizontal structure in this region varies over the upwelling season (fig. 23a–d). In April, the near-surface temperature is nearly homogeneous (fig. 23a): only the coastal waters near Cape Blanco show the obvious influence of coastal upwelling. In July, the inshore band of water cooler than 10°C extends along the entire coast from 42° to 45°N , but this band is clearly wider at the California border than off central Oregon, and coldest waters are observed in the lee of Cape Blanco. In September, the inshore strip is less homogeneous, but the band cooler than 13°C is still widest downstream of Cape Blanco, though the 13°C isotherm has already crossed the shelf break near Heceta Bank at 44°N .

Maps of dynamic topography (fig. 23b) show strong southward flow. In April, this southward current was restricted to the continental margin, and it was particularly narrow off Newport, where it was confined to the

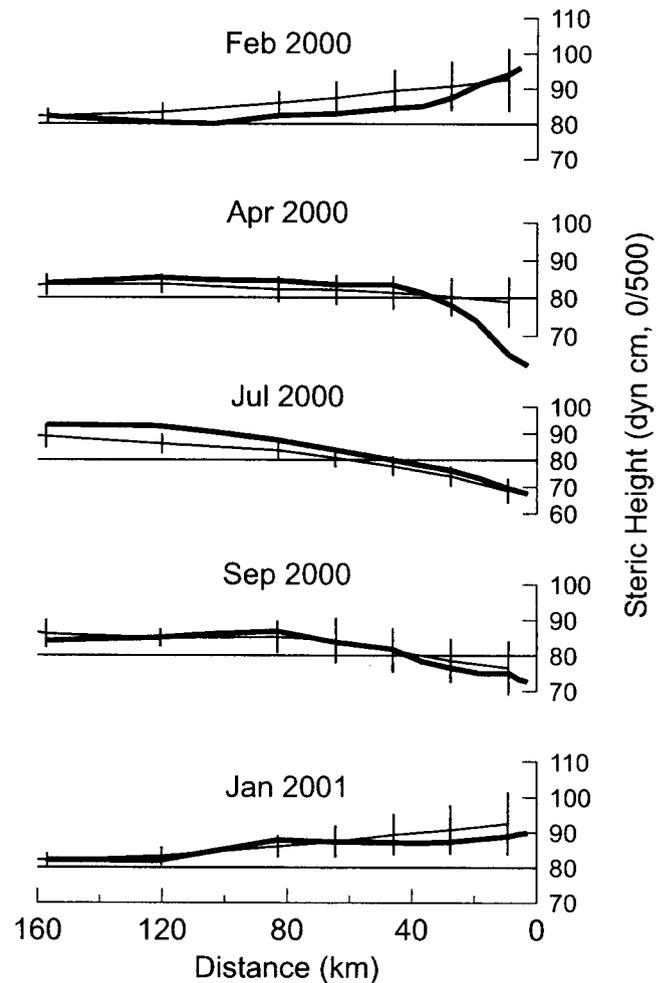


Figure 21. Steric height profiles of the sea surface (relative to 500 dbar) along the NH line at 44.65°N during 2000–2001 (heavy line) shown with the long-term (1961–71) seasonal or monthly average provided by Smith et al. (in press). Vertical bars indicate one standard deviation above and below the average at each standard station. Steric height values over the shelf and upper slope were calculated by the method of Reid and Mantyla (1976).

shelf. By July, the current was wider; off Crescent City, the core of the current lay near 126°W , the offshore end of our section. By September, the current over the continental margin was much weaker, and two cyclonic eddies had formed: one off Crescent City and one near Heceta Bank.

The surface salinity distributions (fig. 23c) confirm southward advection along the coast. The only large source of fresh water in the region is the Columbia River, whose mouth is at 46.25°N , 180 km north of Newport. The Columbia estuary is strongly stratified during the high-flow spring and summer seasons, and it is not uncommon for surface salinities at the mouth to be less than 25 psu (Jay and Smith 1990). The salinity at the core of the plume increases gradually with distance from the mouth, but the plume remains discernible from the background of subarctic surface waters so long as salin-

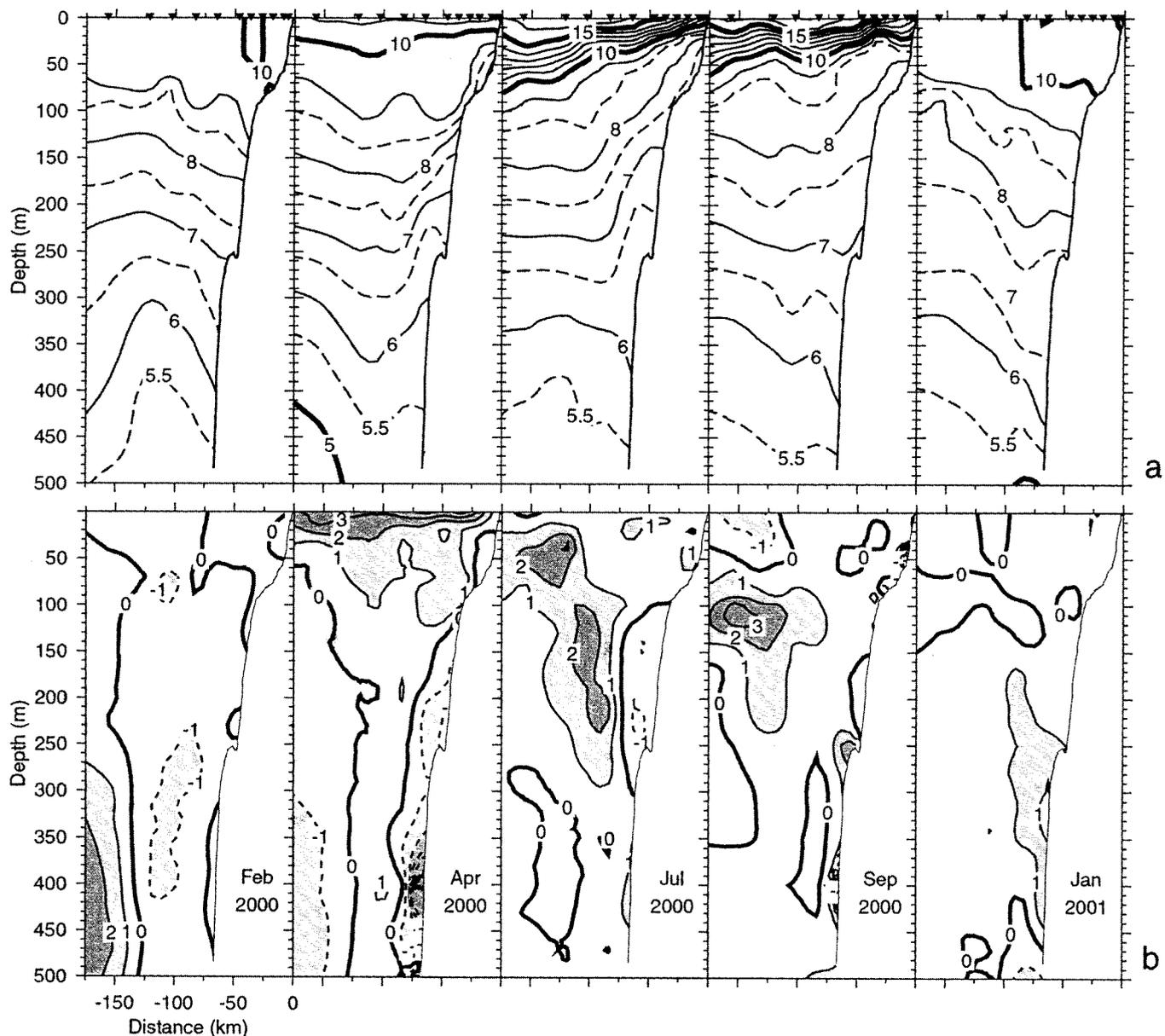


Figure 22. a, Temperature along the NH line at 44.65° N. Inverted triangles at top show the location of CTD stations. b, Normalized temperature anomalies for the NH line at 44.65° N. Positive (negative, dashed contours) anomalies indicate that present values are warmer (colder) than the historical (1961–71) seasonal or monthly averages. Values greater than 1 (2, 3) are significant at the 90% (95%, 99%) level.

ity remains less than 32.5 psu (Barnes et al. 1972). In April, minimum surface salinities (<31.5 at several stations) occurred over the continental margin, consistent with the strong coastal current inferred from the dynamic topography (fig. 23b); subarctic Pacific waters ($S > 32.5$) were observed at the offshore end of each section. By July, the core of the Columbia River plume lay farther from shore, and high-salinity, freshly upwelled waters ($S > 33.5$) lay adjacent to the coast. By September, the Columbia River plume was quite diffuse, and coastal salinities had decreased, though inshore values remained significantly higher ($S > 33$) than the offshore background of subarctic water.

The 10 m chlorophyll distributions (fig. 23d) strongly reflect the influence of coastal upwelling. In April, maximum values of chlorophyll coincide roughly with the inshore locations of minimum temperature (<10.5°C) and maximum salinity (~33 psu); highest values along the NH line in February 2000 were all less than 1 mg/m³. In July, the high-chlorophyll region (>2 mg/m³) coincides well with the region of high-salinity coastal waters ($S > 33$ psu). In September, chlorophyll values are substantially reduced, but still relatively high in the coastal strip (except at 42°N, where values were <1 at all stations).

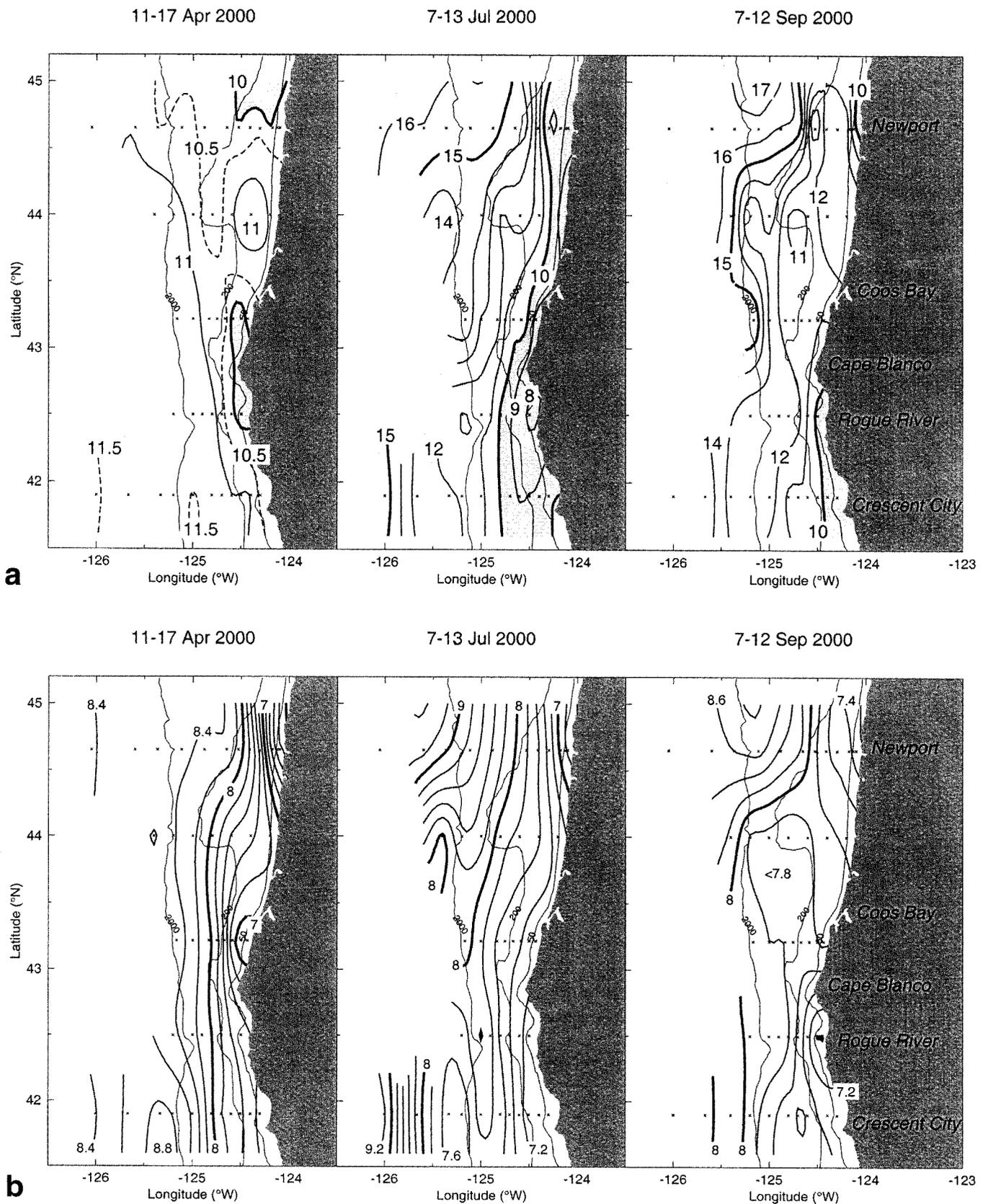


Figure 23a, b. (See next page for 23c and d.) Spatial patterns for GLOBEC LTOP cruises: a, 10 m temperature; b, geopotential anomaly (J/kg) of the sea surface relative to 500 dbar. Values over the shelf and upper slope were calculated by the method of Reid and Mantyla (1976).

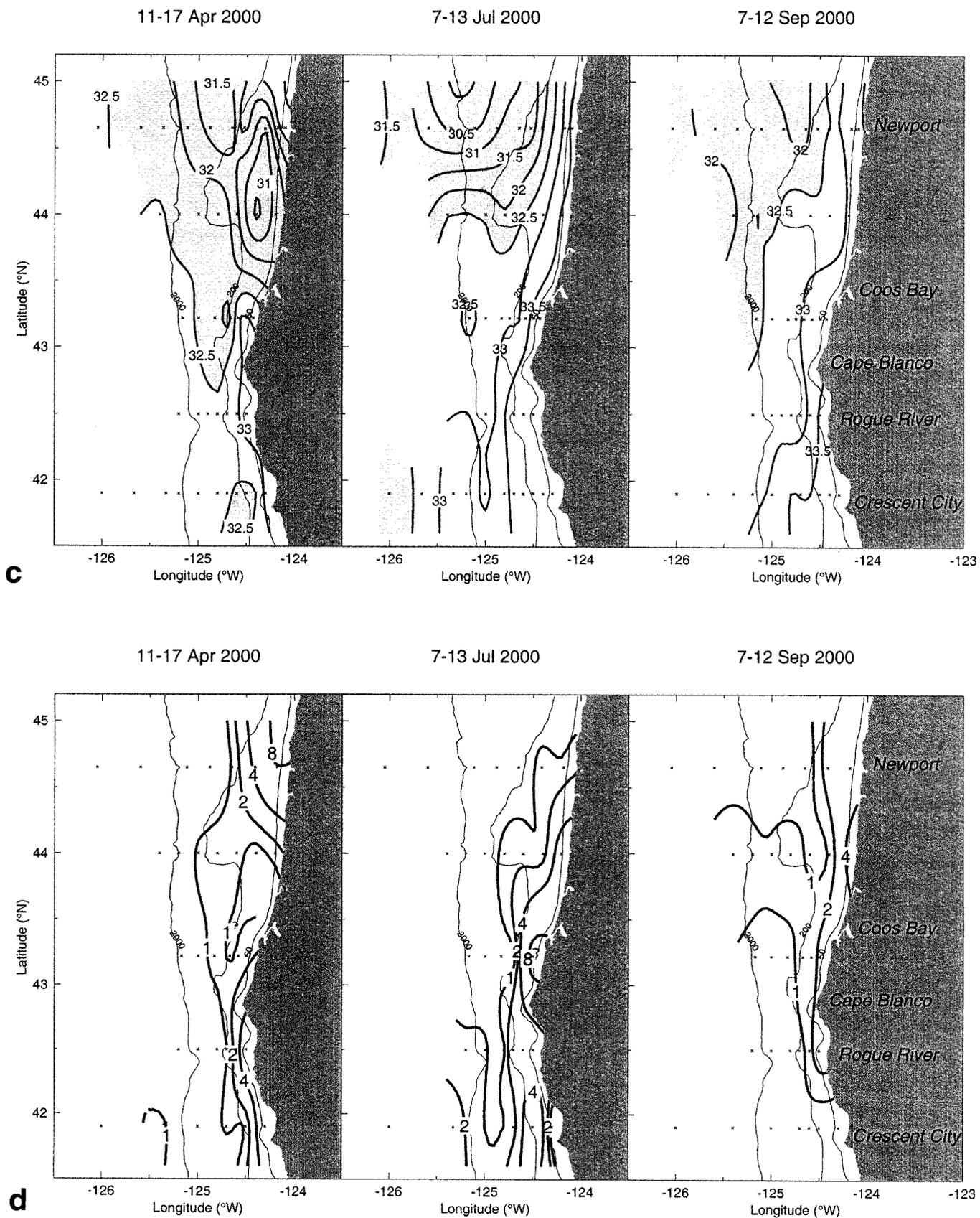


Figure 23c, d. Spatial patterns for GLOBEC LTOP cruises: c, 10-m salinity (psu) and d, 10 m chlorophyll a (mg/m^3).

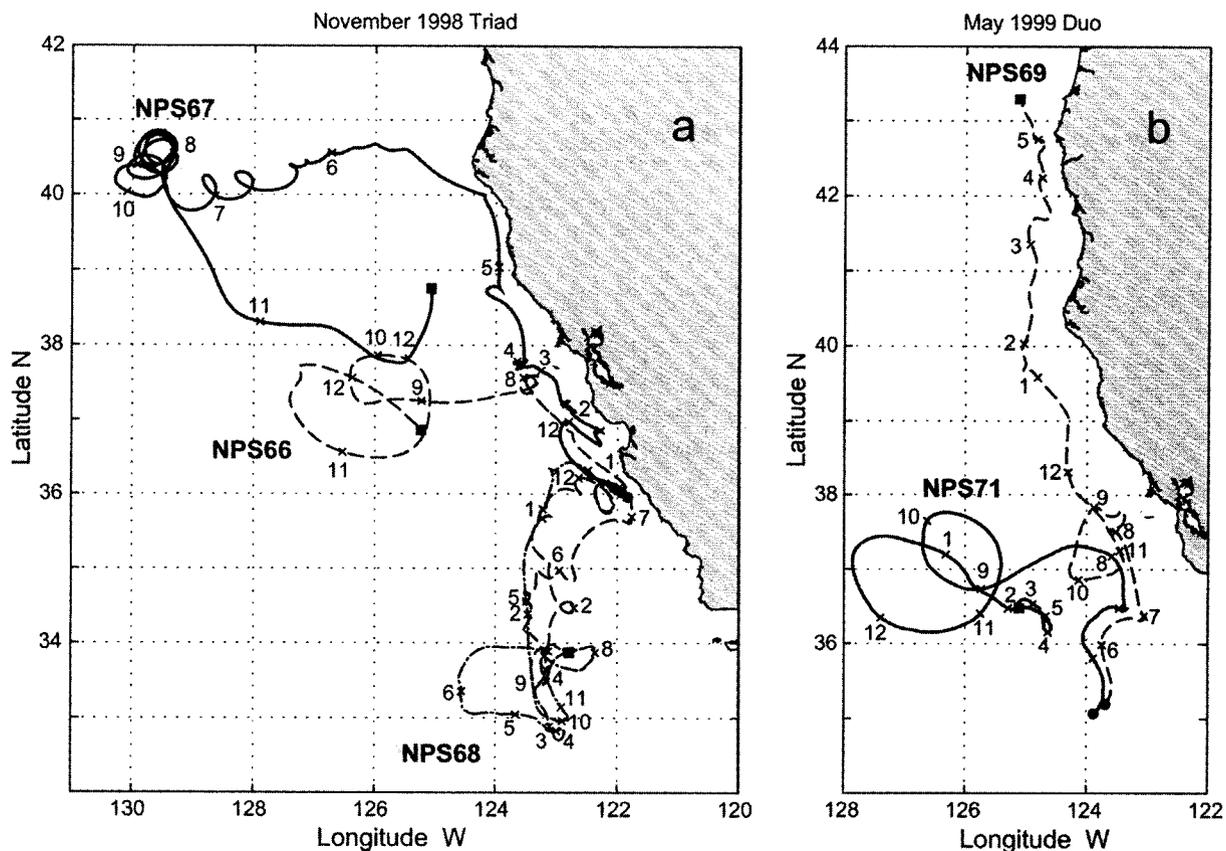


Figure 24. Subsurface (400 dbar) drifter trajectories of NPS RAFOS floats deployed in November 1998 and May 1999. The launch sites are indicated by solid circles; the location where each float surfaced is indicated by solid squares. Numbers along the trajectories denote month of the year. Note the different latitudinal ranges on the two frames.

DRIFTER STUDIES

The subsurface poleward flow of the California Undercurrent (CU) is generally topographically constrained to the continental slope (Lynn and Simpson 1987). The CU is relatively narrow, and peak speeds occur in relatively shallow water (~150 m) above the continental margin. In order to obtain Lagrangian estimates of the current it is necessary to have floats that are navigated in situ underwater, not floats that surface for a position determination and then resubmerge for transport by the current. While at the surface, the latter type of float would be advected offshore, out of the CU. For this reason, the RAFOS technology (Rossby et al. 1986) is the most appropriate way to measure the flow defining the CU.

Lagrangian trajectories for isobaric (400 dbar) subsurface floats that completed their mission in 2000 are shown in figure 24. Previously, trajectories have fallen into three patterns: poleward flow along the coast, along-shore reversing flow, and offshore flow in eddies (Garfield et al. 1999). For floats launched in November 1998, poleward flow along the coast was observed from January through May 1999 for NPS67 and from mid-July to

mid-August 1999 for NPS66 (fig. 24a). NPS67 left the coast to the south of Cape Blanco, and moved rapidly offshore in June in a jet that became unstable at 127°W; as it moved farther west, it became entrained in a nearly stationary eddy near 40.5°N, 130°W from August through October. After November launch, floats NPS66 and NPS68 moved southward until March, when NPS66 returned northward (reaching the coast in July) and NPS68 remained near 33.5°N, 123°W.

The two floats launched in May 1999 followed similar trajectories until August 1999, when NPS71 moved westward and was entrained in an anticyclonic eddy in September (fig. 24b). NPS71 made two loops around the eddy before leaving the eddy at 126°W in February; it subsequently moved very slowly, remaining near 36.5°N, 125°W. In August 1999, NPS69 became entrained in an anticyclonic eddy near 37.5°N, 124°W, but after one loop around the eddy, it reentered the poleward flow along the coast in November 1999, transiting to 43°N and surfacing in June 2000.

These float releases show two types of flow that had not been observed earlier: extensive onshore flow (as opposed to shoreward flow as a portion of flow around

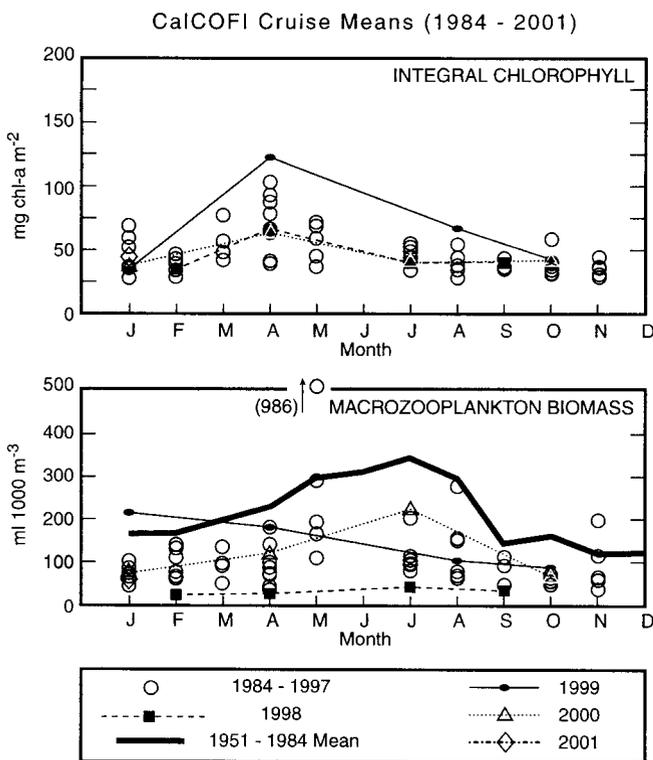


Figure 25. Cruise means of vertically integrated chlorophyll and macrozooplankton biomass plotted versus the month for CalCOFI cruises from 1984 to January 2001. Each point represents the mean of all measurements on a cruise (usually 66). Open circles indicate the cruises that took place from 1984 to 1997. The solid symbols are cruises from 1998 and 1999; cruises from individual years are connected with lines. The bold line in macrozooplankton biomass indicates the monthly means for 1951–84.

an eddy) and small-scale cyclonic motion. The former behavior was exhibited by both NPS67 and NPS66, but at different times of the year. Because of smoothing, the small-scale (10 km) cyclonic motion of NPS66 is difficult to see in figure 24a. NPS66 enters this eddy shortly after launch in November 1998, and makes 12 rotations before leaving the eddy in June 1999.

BIOLOGICAL PATTERNS

Chlorophyll and Macrozooplankton

Cruise-mean values of vertically integrated chlorophyll *a* and macrozooplankton biomass for April 2000 through January 2001 are given in the context of the historical CalCOFI time series (fig. 25). As described in last year's report and elsewhere (Bograd et al. 2000; Bograd and Lynn 2001; Lynn and Bograd, in press), there was a dramatic transition in both the physical and biological environment of the CCS between El Niño (1997–98) and La Niña (1998–99) periods. Zooplankton biomass was the lowest ever recorded throughout 1998, but rebounded strongly in the winter and spring of 1999 (Bograd and Lynn 2001). The biological patterns on the 2000 and January 2001 cruises generally fell between the

extremes of 1998 and 1999. Chlorophyll production was much lower in the spring and summer of 2000 than it had been the previous year, but was near normal levels. Zooplankton biomass was high in July 2000, but below the levels of 1999 for the other cruises. It does not appear that the dramatic rebound in secondary production observed in 1999 was a precursor to a reversal in the long-term decline of zooplankton in the CCS.

Sardine Spawning

The use of CUFES on CalCOFI surveys was begun in 1996. Results from CUFES now provide annual updates on the location, dimensions, and general character of the spawning habitat of the sardines and anchovies. Mapping of sardine and anchovy egg distributions show that sardine spawning had spread to offshore areas of the California Current north of Point Conception by spring 1996. In contrast, anchovy eggs were found farther inshore, mainly limited to the region of the Southern California Bight, and were much less abundant (Checkley et al. 2000). The 1997 survey showed sardine spawning again located offshore, and distributed from the southernmost CalCOFI line to the area off Monterey in central California. The sardine egg concentrations were again higher north of Point Conception, while the anchovy spawning was much lighter and limited to the Southern California Bight area (Checkley et al. 2000). In the spring of 1998 there was a discernible northward shift in the spawning, and the eggs were found in more inshore waters, compressed toward the coast (Lynn et al. 1998) during the period of strong warming associated with El Niño effects on the CC in 1997–98.

Sardine spawning in April 1999, as measured by CUFES, was spread over most of the extended CalCOFI sampling grid, reaching at least to 400 km off central California (fig 26). This offshore expansion of sardine eggs appears to be in response to the highly anomalous conditions that prevailed in the CCS concurrently with the equatorial La Niña. Coastal upwelling reached record proportions in 1999 (Schwing et al. 2000); CC transport was anomalously strong (Lynn and Bograd, in press); and the core of the CC jet was displaced far offshore, as evidenced by the fields of dynamic height and salinity (Hayward et al. 1999). The broad distribution of sardine eggs in April 1999 is in stark contrast to the narrow band of eggs found in April 1998 (Lynn et al. 1998).

On the IMECOCAL surveys, routine use of CUFES began in January 2000. The winter 2000 distribution of sardine eggs in the IMECOCAL region (not shown) was confined mainly to inshore areas from central Baja California southward to Magdalena Bay, where the cruise terminated. Most of the eggs were concentrated in the near-coastal area of the bight just north of Bahía Magdalena (24°N). Only one egg was found in the en-

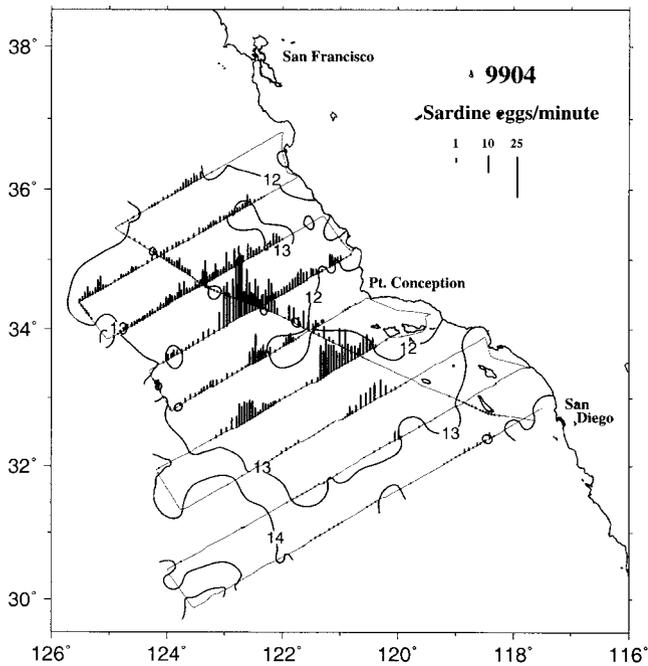


Figure 26. The distribution of sardine eggs as collected by the continuous underway fish egg sampler (CUFES) for CalCOFI survey 9904 (1–20 April 1999).

the CalCOFI region (D. Griffith, pers. comm.). The spring 2000 distribution of sardine eggs in the CC is shown in figure 27, which covers both the CalCOFI and IMECOCAL regions. The eggs were found distributed from just south of Punta Eugenia (approximately 27°N) to the waters offshore of San Francisco, just north of 38°N. However, there is a striking contrast in the concentration and distance offshore of the sardine eggs in the CalCOFI region compared to the IMECOCAL region in figure 27.

In spring 2000, the distribution of eggs was much more extensive from line 93 northward and much more abundant than in the south. The eggs were also found generally farther offshore in the CalCOFI region. There were some scattered occurrences of sardine eggs offshore in the IMECOCAL region between Punta Eugenia and Punta Baja, but most eggs were found near shore. Unfortunately, the transition in the pattern of distribution from north to south is obscured by the lack of sampling along line 97 in the space between the CalCOFI and IMECOCAL surveys. The change in distribution appears to coincide with the onshore sweep of the CC seen in the April 2000 dynamic heights (fig. 20) and may be related to an abrupt change in available food for spawning adults, in relation to the presence of a recurrent anticyclonic eddy southwest of Point Conception (Haury et al. 1986; Pelaez and McGowan 1986). Compared to April 1999 (fig. 26), the sardine eggs in April 2000 were found in higher concentrations farther north. The offshore extent of eggs in the spring 1999 CalCOFI

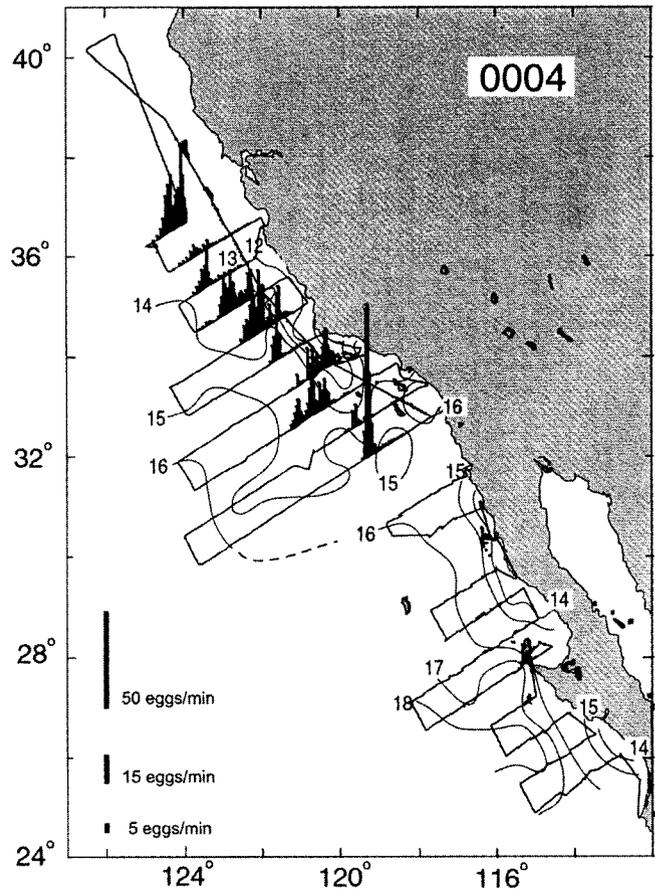


Figure 27. The distribution of sardine eggs as collected by the continuous underway fish egg sampler (CUFES) for CalCOFI and IMECOCAL surveys of April 2000.

survey was much greater, reaching to the end of almost all the lines north of Point Conception. The more compressed onshore distribution and occurrence farther north in spring 2000 compared to spring 1999 coincided with the mild warming of the CC and return to more normal conditions after the cool La Niña period in the CC.

Avifauna

Vessel-based surveys since 1987 have revealed that seabird populations respond to interannual (e.g., El Niño/La Niña events) and longer-term (e.g., decadal ocean warming) variability in the properties of the California Current (Ainley 1976; Veit et al. 1996; Hyrenbach 2001). Colony-based studies of seabird demography and diets underscore the results of at-sea surveys. The PRBO Marine Science Program has monitored the reproductive performance of seabird populations breeding at the Farallon Islands (central California) since the early 1970s. These long-term studies have revealed that locally breeding marine bird populations are sensitive to fluctuations in ocean productivity and prey availability (Ainley et al. 1995; Sydeman et al., in press).

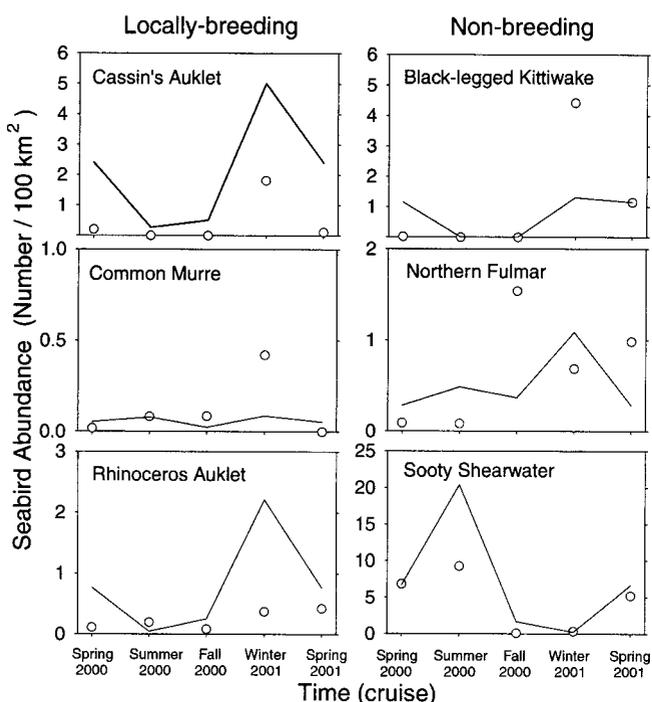


Figure 28. Abundance of three locally breeding and nonbreeding seabird species with an affinity for cold water between spring 2000 and spring 2001. For reference, the line indicates the long-term means of seasonal abundance (spring 1990–spring 2001).

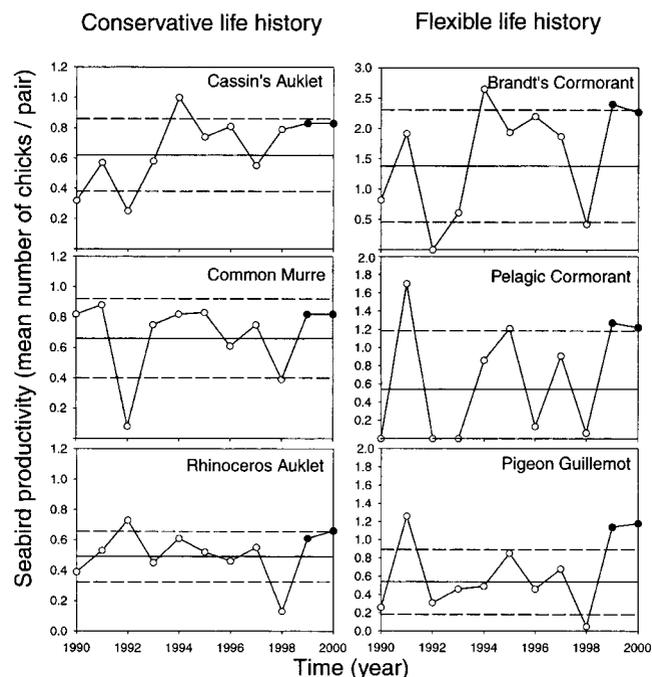


Figure 29. Anomalies of productivity for six seabird species breeding at Southeast Farallon Island (central California). The long-term averages (1990–2000) are depicted by the solid lines; the hatched lines illustrate the variability (mean \pm SD). Filled circles highlight productivity anomalies after the hypothesized regime shift during the winter of 1999.

TABLE 3
 Changes in Abundance of Six “Cold-Water” Seabird Species in the CalCOFI Study Area, in Conjunction with the Hypothesized Regime Shift during Winter 1999

Seabird species	Abundance (birds/100 km ²) (mean \pm SD)		Proportional change (%) ^a	Mann-Whitney U	p value
	(1990–1998)	(1999–2001)			
Black-legged kittiwake	0.47 \pm 1.54	1.17 \pm 1.77	+146	124.5	0.710
Cassin's auklet	2.33 \pm 4.19	0.34 \pm 0.61	-85	194	0.063
Common murre	0.05 \pm 0.12	0.07 \pm 0.14	+39	144	0.796
Northern fulmar	0.54 \pm 0.93	0.45 \pm 0.56	-16	195	0.059
Rhinoceros auklet	0.91 \pm 1.78	0.17 \pm 1.15	-81	215	0.011
Sooty shearwater	7.47 \pm 1.22	6.31 \pm 6.17	-15	144	0.798

Comparison of standardized seasonally adjusted anomalies of abundance “before” (34 cruises between winter 1990 and fall 1998) and “after” (8 cruises between winter 1999 and spring 2001) the regime shift.

^aQuantified as PC = 100% * [(before) - (after)]/(before).

Vessel-based surveys between spring 2000 and spring 2001 did not reveal concurrent increases in the abundance of cold-water seabird species. In fact, only four of the six taxa considered surpassed their long-term (spring 1990–spring 2001) abundance during at least one cruise (fig. 28). The locally breeding common murre (*Uria aalge*) increased in abundance during the winter, and the rhinoceros auklet (*Cerorhinca monocerata*) increased in the summer. But the most numerous locally breeding species—the Cassin's auklet (*Ptychoramphus aleuticus*)—remained well below its long-term abundance. Non-breeding species behaved similarly, with sporadic increases during certain cruises. For instance, we documented

positive anomalies of black-legged kittiwake (*Rissa tri-dactyla*) abundance during winter 2001. On the other hand, the northern fulmar (*Fulmarus glacialis*) was most abundant during fall 2000 and spring 2001. Conversely, the once numerically dominant sooty shearwater (*Puffinus griseus*) consistently remained below its long-term abundance. Overall, we detected no significant increases in the abundance of cold-water seabirds after the winter of 1999 (table 3).

Surveys of six seabird species breeding at the Farallon Islands revealed high reproductive performance during 2000, following large increases between 1998 and 1999 (fig. 29). In 1998, only the productivity of the Cassin's

TABLE 4
 Changes in the Productivity of Six Seabird Species Breeding at the Farallon Islands (Central California),
 in Conjunction with the Hypothesized Regime Shift during Winter 1999

Seabird species	Productivity (chicks fledged/pair) ^a (mean±SD)		Proportional change (%) ^b	Mann- Whitney U	p value
	(1990–1998)	(1999–2001)			
Brandt's cormorant	1.38 ± 0.93	2.33 ± 0.09	+69	2	0.098
Cassin's auklet	0.62 ± 0.24	0.83 ± 0.00	+33	2	0.098
Common murre	0.66 ± 0.27	0.82 ± 0.00	+24	6	0.468
Pelagic cormorant	0.54 ± 0.64	1.24 ± 0.03	+130	0	0.034
Pigeon guillemot	0.54 ± 0.38	1.16 ± 0.03	+117	2	0.098
Rhinoceros auklet	0.48 ± 0.16	0.63 ± 0.03	+31	2.5	0.124

Comparison of the average seabird productivity "before" (1990–1998) and "after" (1999–2000) the regime shift.

^aExpressed as the mean number of chicks fledged per nest during the breeding season.

^bQuantified as PC = 100% * [(before) - (after)] / (before).

auklet surpassed its long-term (1990–2000) average. Conversely, in 1999 and 2000, we recorded positive productivity anomalies for all six taxa analyzed. In particular, the productivity of three species with more "flexible" life histories—Brandt's cormorant (*Phalacrocorax penicillatus*), pigeon guillemot (*Cepphus columba*), and pelagic cormorant (*Phalacrocorax pelagicus*)—was markedly higher (anomalies exceeding one standard deviation) after the hypothesized regime shift during the winter of 1999. Overall, we detected a significant increase in the productivity of the pelagic cormorant, and documented increases that were marginally significant ($0.10 < p < 0.05$) for three other species (pigeon guillemot, Brandt's cormorant, and Cassin's auklet; table 4).

The analysis of marine bird populations breeding at the Farallon Islands (central California) revealed increases in seabird productivity during 1999 and 2000, when compared to conditions during the preceding warm-water regime (1990 through 1998; table 3). However, this demographic response varied according to species-specific life-history characteristics. The Brandt's cormorant, pigeon guillemot, and pelagic cormorant showed the strongest response in productivity after the winter of 1999. In fact, for the pigeon guillemot and the pelagic cormorant, the mean number of chicks successfully fledged by a breeding pair more than doubled between 1990–98 and 1999–2000. These species have broad diets, inhabit neritic waters and estuaries, and have been shown to respond very strongly to enhanced prey availability off central California (Ainley et al. 1995; Sydeman et al. 1997, in press). On the other hand, the productivity of seabird species with more "conservative" reproductive strategies and restricted dietary and habitat preferences increased only slightly (24%–33%) during 1999 and 2000. The Cassin's auklet, common murre, and rhinoceros auklet forage along the continental shelf, where they feed largely on juvenile rockfish (*Sebastes* spp.), anchovies (*Engraulis mordax*), and cold-water euphausiids (*Euphausia pacifica* and *Thysanoessa spinifera*; Sydeman et al. 1997).

Vessel-based surveys and demographic research at colonies suggest that seabird distributions and productivity are influenced by interannual variability in the properties of the California Current. The productivity of locally breeding seabirds increased during 1999 and 2000, apparently in response to enhanced upwelling and ocean productivity (Ainley et al. 1995; Sydeman et al., in press; figs. 6 and 25). Moreover, far-ranging cold-water seabirds became more numerous off southern California in response to cool ocean temperatures (fig. 4) and increasing primary and secondary production (fig. 25) during 1999 (Hayward et al. 1999; Bograd et al. 2000). Subsequently, these species vacated the region as a result of declining productivity during 2000.

These findings underscore the notion that life-history traits constrain the ability of seabirds to respond to climatic fluctuations. In particular, differences in mobility and adaptability modulate species-specific responses to changing ocean temperature and food availability. Seabirds are highly mobile marine predators capable of shifting their foraging ranges in response to changes in ocean productivity and water-mass distributions (Ainley 1976; Veit et al. 1996). Additionally, the ability of breeding seabirds to enhance their reproductive success during periods of elevated ocean productivity and prey availability appears to be influenced by species-specific habitat and dietary preferences (Ainley et al. 1995; Sydeman et al., in press).

However, it remains unclear to what degree physical-biological interactions influence the ability of seabird populations to cope with climatic variability via behavioral (e.g., redistribution) and demographic (e.g., reproductive success) mechanisms. The integration of CalCOFI at-sea surveys and PRBO colony-based studies will enhance our knowledge of the mechanisms linking oceanographic forcing, prey availability, and seabird demography. Understanding the way marine bird dispersion and foraging opportunities influence reproductive success is essential for anticipating the response of seabird populations to oceanographic variability in the highly variable CCS.

DISCUSSION

As indicated by the MEI (Wolter and Timlin 1998), the period from January 2000 to May 2001 marked the third consecutive year in which a weak to moderate La Niña state persisted over the tropical Pacific. The observations described here, however, indicate that from Oregon to Baja California, the oceanographic conditions within the CCS were not significantly warmer or colder than the climatological mean. Zooplankton biomass, which rebounded to high levels in 1999 after a decline during El Niño, showed near normal values during 2000–2001. Likewise, seabird surveys did not reveal persistent increases in the abundance of cold-water species off southern California. The numerically dominant locally breeding (Cassin's auklet) and visiting (sooty shearwater) seabirds remained consistently below their long-term seasonal abundance. These species have declined significantly over the long term off southern (1987–98) and central (1985–94) California (Hyrenbach 2001; Oedekoven et al. 2001).

Record low coastal sea level associated with extremely high levels of coastal upwelling for northern California in 1999 (Schwing et al. 2000), as well as the rebound in zooplankton abundance from the lowest in the CalCOFI record to above normal levels (Bograd et al. 2000) have been suggested as possible indicators of a North Pacific warm-cold regime shift in 1998–2000. Is this hypothesized cold-water regime manifested in the CCS? The answer is not straightforward.

Over the last decade, there has been an increased interest in studying the response of ecosystems to recurrent patterns of atmosphere–ocean climate variability on decadal and interdecadal scales. Changes in environmental variables and departures from normal conditions due to climate shifts have been shown to modify zooplankton biomass (Roemmich and McGowan 1995), fish stocks (Mantua et al. 1997), and seabirds (Hyrenbach 2001; Oedekoven et al. 2001). Moreover, a climate transition brings changes in the mechanisms that regulate the ecosystem, but these changes are virtually impossible to characterize at the time they occur (Mantua et al. 1997). Since stepwise climate shifts occur on an average of every 23 years (Gedalof and Smith 2001), and since the last shift took place in 1976–77 (Mantua et al. 1997), it is very tempting to associate dramatic changes in the CCS ecosystem with a period of climate transition. The observations presented here, while not yet supporting the notion of a transition to a cold-water regime of enhanced upwelling and elevated production, do provide a proxy for understanding how the CCS may respond to future interannual changes and decadal climate shifts. The uncertainty of the different indicators used as a proxy for climate shifts not only highlights the need for continuing and expanding the CalCOFI monitoring, but also emphasizes the value of long-term observations.

The constriction of the CalCOFI program in 1984 (Hewitt 1988) to the region delimited in figure 1, while adequately resolving some of the temporal variability critical for describing the biophysical response to inter-annual climate forcing, compromises our knowledge of spatial variability over the system by greatly reducing the active area of the sampling grid. The IMECOCAL and GLOBEC-LTOP programs, when coordinated with CalCOFI, provide much of the extra spatial coverage needed to describe fundamental changes in the physical and biological structure over the extent of the CCS (figs. 20 and 27). These programs may also provide better estimates of the abundances of commercially important species, as well as better descriptions of the significant latitudinal shifts in their ranges.

Besides the clear utility of having concurrent measurements along the CCS, from Canada to Baja California (see dynamic height anomalies in fig. 20), the recent developments in oceanographic instrumentation are particularly important, because they allow us to observe in near-real time the spatial distributions of organisms. Sardine egg distributions as measured by the CUFES system presented above (fig. 27) are an excellent example of the importance of simultaneous measurements. Continuing this type of monitoring will undoubtedly improve our knowledge of this and other species' abundance. The preliminary results shown here, however, have raised additional questions. For example, why did sardines spawn only in the coastal regions surrounding Punta Eugenia and not at all off California during January 2000, while the reverse was true during spring 2000? What kind of physical interactions define the ideal spawning conditions? Are fronts and coastal enrichment by upwelling and eddies the key processes that determine egg distributions? Are there any rapid responses of predators to the presence or absence of sardine eggs, or is predator dispersion controlled mainly by currents?

After 52 years of the CalCOFI program, it still remains unclear to what degree physical–biological interactions influence the ability of marine populations to cope with climatic variability via behavioral (e.g., redistribution) and demographic (e.g., reproductive success) mechanisms. The expansion of the new monitoring methodologies and the future integration of the large suite of environmental data that is now being routinely collected along the CCS, from northern California and Oregon to Baja California, will certainly enhance our knowledge of the mechanisms linking environmental change with marine ecosystem response.

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Part II

SYMPOSIUM OF THE CALCOFI CONFERENCE, 2000

Lake Arrowhead, California
1 November 2000

ECOSYSTEM-BASED FISHERY MANAGEMENT IN THE NEARSHORE ENVIRONMENT

Ecosystem-based management has been proposed as an improvement over single-species resource management approaches. Yet at this point, we are still grappling with what ecosystem-based management is and how it can be meaningfully applied. We need to understand how ecosystem-level factors interact with fishing to impact stocks (Beamish and Mahnken 1999). In order to be an improvement over single-species management, ecosystem-based management should incorporate ecosystem-level effects on fishing, oceanographic conditions, and multiple interspecific interactions (including positive interactions) to protect against fishery collapse.

Ecosystems are difficult to define, but most definitions include the interactions among the biological and physical components within a definable geographical unit (Lincoln et al. 1998). In addition, ecologists have discussed the possibilities that such interactions manifest emergent properties—an ecosystem correlate often defined by the holistic euphemism: The whole (ecosystem) is greater than the sum of its parts (species). These interactions presumably also contribute to poorly defined concepts such as “ecosystem health,” “ecosystem integrity,” and “intact” ecosystem (Simberloff 1998). Because many of these concepts have yet to be quantified, they are difficult for resource managers to implement (Larkin 1996). Furthermore, once communities within ecosystems are defined by managers, large-scale shifts in climate (or oceanographic) conditions may rearrange species components (Hunter et al. 1988). Nevertheless, the Sustainable Fisheries Act of 1996 calls for each of the major ecosystems in the United States to be managed using an ecosystem-based approach.

The Ecosystem Principles Advisory Panel convened by the National Marine Fisheries Service has recommended the development of fishery ecosystem plans (FEPs) as a tool to apply ecosystem principles to fisheries conservation, management, and research. These plans are envisioned to coordinate management of existing single-species or species-complex fishery plans, and in the near future managers may be charged with

plan development. Implementing FEPs will involve considering species interactions such as those between predators and prey; minimizing the effects of fishing on essential habitat; and considering how bycatch affects the food web and community structure. In order to apply these principles, control rules that must be both practical and enforceable will be drafted, with constituent involvement. One way to apply ecosystem management is through the use of marine protected areas, which are currently the focus of considerable research (Lauck et al. 1998). Ultimately, it is hoped that FEPs will be superior to single-species management approaches.

There is increasing concern that fishing has negative consequences for marine ecosystems (Dayton et al. 1995). Numerous impacts of fishing have been identified, including effects on target and nontarget species, habitat alterations, and changes in the trophic structure of marine communities. Fishing can affect target species by changing age and size structure, sex ratios, and the genetic structure of fished populations (Botsford et al. 1997). Habitat alterations have been attributed to trawling gear (Auster et al. 1996; Engel and Kvitek 1998), and it is estimated that seabed disturbances on the continental shelf each year are 150 times greater than disturbances resulting from clear-cutting in the terrestrial landscape (Watling and Norse 1998). In terrestrial environments we know that logging can affect habitat function by uncoupling nutrient cycling, which leads to a loss of nutrients and productivity (Likens and Bormann 1975). In marine systems, fishing in coral reef communities has been shown to lead to the loss of reef processes such as the accretion of calcium carbonate (Roberts 1995). Fishing removes “engineering” organisms (*sensu* Jones et al. 1997) that directly or indirectly control the availability of resources to other organisms in the community. The loss of ecosystem engineers to fishing affects habitat function by reducing structural complexity and species diversity (Leichter and Witman 1997). For example, the reduction of oyster beds through mechanical harvest leads to enhanced hypoxic conditions in

summer, killing economically important blue crabs (Lenihan and Peterson 1998). Loss of species diversity may alter the structure of communities—potentially rendering these communities, and the fish stocks within them, more vulnerable to perturbations (Roberts 1995). Changes in the structure of trophic webs have been described for heavily fished ecosystems with the near removal of higher-trophic-level predators (Pauly et al. 1998). Are these changes affecting the resilience of marine communities? Do multiple stable states exist in marine systems, some states supporting fished species and other states supporting species with little economic value, such as jellyfish (C. Mills, Friday Harbor Laboratories, Univ. Washington, pers. comm.)?

Overlying the effects of fishing are large-scale oceanographic changes such as the regime shift of 1976–77 (Francis and Hare 1994; Mantua et al. 1997). Oceanographic conditions impact whole systems, such as the California Current, and CalCOFI has made major contributions to our understanding of the ecological consequences of these events. Dramatic reductions in zooplankton (Roemmich and McGowan 1995; McGowan et al. 1998) and other sources of larval fish food affect fishery productivity. Hypotheses that may link ocean conditions to fish abundance are now being proposed, such as the critical size/critical period hypothesis, which suggests that salmon stocks are driven by the growth rates of juveniles in the ocean in summer (Beamish and Mahnken 1999). Surely, multiple species and indeed whole ecosystems are altered during major El Niño events, such as that of 1997–98, which was the focus of the 1999 CalCOFI symposium (Mullin 2000). Recently, oceanographic conditions have been incorporated into fishery management plans because the productivity of many stocks seems to be correlated with temperature, with some stocks more productive during warm regimes and other stocks during cold regimes. For example, the 2001 management guidelines for Pacific sardine incorporate sea-surface temperature (average of preceding three years) into the computation of the allowable catch, which is lower in cold (less productive) years and higher in warm years (Conser et al. 2001).

Species interactions are currently incorporated into ecosystem-based models within food webs. Since the focus of species interactions in food webs is primarily predation, the assumption is that the total yield from a multispecies model, such as virtual population analysis, will necessarily be less (due to predation) than the sum of the maximum yields of the component species models (but see Brander and Mohn 1991). Given these limitations, some researchers have questioned whether multispecies models will yield superior management advice compared with single-species models (Magnusson 1995). Multispecies models should incorporate positive

species interactions (sensu Bertness and Leonard 1997). These revisited models may yield practical results on the emergent properties of communities, and novel management options may come to light. For example, the presence of red sea urchins in marine protected areas enhanced the abundance of juvenile abalone compared to fished areas, indicating that sea urchin harvest refugia may enhance the recruitment of abalone (Rogers-Bennett and Pearse 2001). The challenge will be to quantify ecosystem functions and positive species interactions (emergent properties) and incorporate these parameters into ecosystem-based management.

The papers that follow are based on the presentations given at the symposium entitled Ecosystem-Based Fishery Management in the Nearshore Environment. (Several of the presentations were not submitted as papers.) The recommendations of the Ecosystem Principles Advisory Panel are detailed in the first paper of this symposium. The second paper characterizes the biological dynamics of the northern California Current ecosystem (NCCE), the development of a conceptual model of the food web, and an estimation of total removals and how they relate to standing biomass, production, and trophic structure. The authors use Ecopath models to compare the NCCE during a cool regime in the 1960s to the warm regime in the 1990s. The third paper describes the practical application of an ecosystem model for multiple fisheries in a coastal lagoon system and how such models can be used to determine which fishing strategies optimize yields. Finally, a simulated oil spill in the California Current ecosystem is described, and a number of response options, including the use of chemical dispersants, are evaluated. The papers from this symposium were refereed by at least two peer reviewers and edited by Laura Rogers-Bennett and Julie Olfe.

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IMPLEMENTING ECOSYSTEM-BASED MANAGEMENT OF FISHERIES IN THE CONTEXT OF U.S. REGIONAL FISHERIES MANAGEMENT: RECOMMENDATIONS OF THE NMFS ECOSYSTEM PRINCIPLES ADVISORY PANEL

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ABSTRACT

The Sustainable Fisheries Act of 1996 requires the National Marine Fisheries Service (NMFS) to convene an expert panel to assess the current application of ecosystem principles in U.S. fisheries conservation, management, and research and to make recommendations for increasing their application. The panel identified eight ecosystem principles and six associated policies for ecosystem-based fisheries management, with the goal of maintaining ecosystem health and sustainability. These principles, policies, and goals were used to evaluate current fisheries management practices in the United States. The panel concluded that there are some encouraging examples of ecosystem approaches, but they are limited in scope and not comprehensive. Similarly, U.S. fisheries research tends to parallel traditional single-species fisheries management, although notable ecosystem research is being conducted.

To increase the application of ecosystem-based management, the panel recommends developing fishery ecosystem plans (FEPs) for each major ecosystem in the U.S. Exclusive Economic Zone (EEZ). These plans will coordinate actions taken under existing single-species or species-complex fishery management plans (FMPs). The panel also proposes enhanced research on (1) the ecosystem effects of fishing, (2) ecosystem trends and dynamics, and (3) institutional and governance aspects of ecosystem-based fishery management. To implement these recommendations, a practical, iterative approach is envisioned which would generate a rapid increase in the use of existing ecosystem knowledge in fisheries management and prioritization of research.

INTRODUCTION

The first commissioner of the U.S. Commission of Fish and Fisheries, Spencer Baird, initiated marine ecological studies as one of his earliest priorities. Seeking to reverse the decline of New England's fisheries in 1871, he argued that our understanding of fish "...would not be complete without a thorough knowledge of their associates in the sea, especially of such as prey upon them or constitute their food..." (Hobart 1995). Baird understood that the presence or absence of fish was related

not only to removal by fishing, but also to the dynamics of physical and chemical oceanography. Despite more than a century of research and fisheries management, we still fall far short of managing marine living resources sustainably in an ecosystem context.

This paper is based on the recommendations of a panel convened to advise the Congress on how to better use ecosystem principles in fisheries management and research. It begins with a brief, baseline description of the U.S. fishery management system and its performance. It then outlines the task of the panel as mandated by Congress and how the panel developed its recommendations. It concludes with a discussion of implementing the recommendations.

U.S. FISHERY MANAGEMENT

Since the 1976 passage of the Fishery Conservation and Management Act (FCMA), later known as the Magnuson-Stevens Fishery Conservation and Management Act (MSFCMA), fisheries in federal waters fall under the management authority of eight regional councils comprising representatives of the fishing interests in the region, state officials, and the federal regional fisheries administrator. The councils' decisions are advisory to the secretary of commerce, who is charged with oversight at the national level and the implementation of decisions through the National Marine Fisheries Service (NMFS). Congress explicitly stated that fishing interests should be represented prominently on the councils because they would understand fisheries concerns and would have to live with the consequences of decisions. Thus, there would be a competitive balancing of interests, and there would be direct incentives to conserve the resource.

The record of fisheries management under the FCMA is mixed. There are resounding successes and some dismal failures. All success and failures are achieved under the same management rules, with access to the same levels of competent science, using the same management structure, and implemented by the same agency. Typically, failure can be traced to councils making decisions based on short-term economic and social pressures and not using the best available scientific advice on how to man-

age fish stocks conservatively and sustainably (Dobbs 2000; Hennessy and Healy 2000).

Fisheries management in the United States is now under internal and external pressure to reform. In 1996, Congress responded to the growing public demand for actions to end overfishing, reduce impacts of fishing on the environment, and avoid bycatch or harm to other marine wildlife by significantly amending the FCMA. The Sustainable Fisheries Act (SFA), as the amendments are known, targets specific ecosystem concerns by ending overfishing, minimizing bycatch, and increasing the councils' authority to protect essential fish habitat (EFH).

With respect to overfishing, Congress changed the formula for defining optimum yield. Councils were no longer permitted to set total allowable catch of fish stocks at higher than maximum sustainable yield (MSY) for economic and social reasons. Congress set MSY as a limit and encouraged councils to be more conservative, noting the inherent difficulties of using MSY itself. Furthermore, the councils had to develop a rebuilding plan for fish stocks that were defined as overfished, to achieve their recovery within ten years. The new requirements for bycatch were intended to deal with the biological harm and waste associated with certain fisheries discarding fish. The Congressional mandate included economic discards and regulatory discards and sought to "minimize bycatch to the maximum extent practicable."

The EFH provisions of the SFA were an attempt by Congress to give the councils more opportunity to protect habitat "essential" to fish. This portion of the act was written very broadly and allowed councils to be proactive in encouraging measures to reduce nutrient run-off into coastal waters and to balance other uses harmful to fish habitats. Most significantly, however, it charged councils with evaluating and avoiding fishing effects on ecosystems.

Besides these ecosystem-oriented amendments, Congress called on the National Academy of Sciences (NAS) to convene studies to examine the use of individual fishing quotas and community development quotas, and to review Northeast (U.S.) fishery stock assessments. (The NAS study on sustaining marine fisheries was initiated earlier; National Research Council 1999.) In addition, the National Marine Fisheries Service was asked to develop an annual report to Congress on incidental harvest (bycatch), to expand Gulf of Mexico red snapper research, and to appoint an ecosystem principles advisory panel.

ECOSYSTEM PRINCIPLES ADVISORY PANEL

The SFA's most direct action to initiate an ecosystem-based management approach was to mandate the formation of the NMFS Ecosystem Principles Advisory Panel. Congress specified that NMFS, with the advice

of the NAS, would appoint a panel to advise Congress on ways to increase the application of ecosystem principles in conservation and management of fisheries. The new panel, consisting of not more than 20 people, would include individuals with expertise in the structures, functions, and physical and biological characteristics of ecosystems, as well as representatives from the regional councils, states, fishing industry, conservation organizations, or others with expertise in managing marine resources. The panel would produce a report that includes an analysis of the extent to which ecosystem principles are being applied in fishery conservation and management activities, including research activities, and would propose actions that should be undertaken by the secretary of commerce and by the Congress to expand the application of ecosystem principles in fishery conservation and management.

After intensive internal and external consultation, the NMFS appointed members to the panel (Appendix). The panel began deliberations immediately. Some of its early decisions set the context for the nature of the report. First, the report would be the product of the panel alone; the NMFS was the convener and provided staff to the panel. Second, the report would be advisory to the Congress and the secretary of commerce. This clarification was important in terms of keeping the target audience in mind. Whereas the earlier NAS study (1999) was meant for a scientific and a broader public audience, the panel report was requested by those who make and implement the rules in fishery management. Third, panel members would write the report on a consensus basis and would control its content. If consensus was not achieved, dissenting members would have an opportunity to explain their views. Fourth, the panel's meetings and discussions would be open to anyone who wanted to participate, and there would be opportunity for public comment. Only the drafts of the report would be treated as confidential to the panel. Finally, the consensus draft would be sent out for peer review, and all panel members would help make changes to the report as requested by the reviewers. Reviewers would remain anonymous to the panel unless they chose to reveal their identities.

Principles

The panel's first task was to agree on what was intended by the term *ecosystem principles*. Congress did not define *ecosystem* or *ecosystem principles*. As might be imagined, this was a difficult task for a disparate panel. We ransacked the literature and our own experience, but realized that no ready-made set of principles could satisfy us, so we set about to construct our own.

The panel clearly agreed that the subject was ecosystem-based management as opposed to ecosystem man-

agement. We regarded “ecosystem-based management” as applying what we know about marine ecosystems and their processes in fisheries management. We felt it was premature to apply “ecosystem management” to marine ecosystems given our state of knowledge and the vast uncertainties. The panel also agreed that effective fishery management, as exemplified by full implementation of the SFA amendments to U.S. fisheries legislation, is a prerequisite for ecosystem-based management. Ecosystem-based management depends on, and cannot substitute for, all of the traditional fishery management tools, the best available scientific information, and the collective political will to implement tough decisions in favor of sustainable fisheries. Ecosystem-based fishery management puts effective management into an ecosystem context.

In developing the principles, we were able to agree that each fisheries ecosystem is unique, but that each ecosystem presents four fundamental problems:

- We do not have a complete understanding of the ecological systems that produce and support fisheries.
- We cannot forecast weather or climate and their effects on ecosystems.
- Systems evolve over time, and knowing how the system works does not necessarily mean that an ecosystem would respond predictably to future changes in the weather, climate, or fisheries.
- Our institutions are not configured to manage at the ecosystem scale. Fish and the fisheries that pursue them are not easily aligned with political and jurisdictional boundaries.

Considering these constraints, the panel developed a set of eight principles that capture our understanding of fisheries ecosystems.

1. The ability to predict ecosystem behavior is limited. Uncertainty and indeterminacy are fundamental characteristics of the dynamics of complex adaptive systems. The behaviors of these systems cannot be predicted with absolute certainty, regardless of the amount of scientific effort invested. We can, however, learn the boundaries of expected behavior and improve our understanding of the underlying dynamics. Thus, while ecosystems are neither totally predictable nor totally unpredictable, we can manage fisheries within the limits of their predictability.

2. Ecosystems have real thresholds and limits which, when exceeded, can affect major system restructuring. Ecosystems are finite and exhaustible, but they usually have a high buffering capacity and are fairly resilient to stress. Often, as stress is applied to an ecosystem, its structure and behavior may not change noticeably at first. Only after a critical threshold is passed does the system begin

to deteriorate rapidly. Because there is little initial change in behavior with increasing stress, these thresholds are very difficult to predict. The nonlinear dynamics which cause this kind of behavior are a basic characteristic of ecosystems.

3. Once thresholds and limits have been exceeded, changes can be irreversible. When an ecosystem is radically altered, it may never return to its original condition, even after the stress is removed. This phenomenon is common in many complex, adaptive systems.

4. Diversity is important to ecosystem functioning. The diversity of components at the individual, species, and landscape scales strongly affects ecosystem behavior. Although the overall productivity of ecosystems may not change significantly when particular species are added or removed, their stability and resilience may be affected.

5. Multiple time scales interact within and among ecosystems. Ecosystems cannot be understood from the perspective of a single time, space, or complexity scale, and the next lower scale of interest must be considered when effects of perturbations are analyzed.

6. Components of ecosystems are linked. The components within ecosystems are linked in complex patterns by flows of material, energy, and information.

7. Ecosystem boundaries are open. Ecosystems are far from equilibrium and cannot be adequately understood without knowledge of their boundary conditions, energy flows, and internal cycling of nutrients and other materials. Environmental variability can alter spatial boundaries and energy inputs to ecosystems.

8. Ecosystems change with time. Ecosystems change with time in response to natural and anthropogenic influences. Different components of ecosystems change at different rates and can influence the overall structure of the ecosystem itself and affect the services provided to society in the form of fish catch, income, and employment.

Goals

It is necessary to have a goal or goals for management to serve. The panel agreed on a simple goal statement: maintain ecosystem health and sustainability. We could not arrive at a consensus definition of ecosystem *health*. We also lacked a common way of defining *sustainability*. We realized that our goal for ecosystem-based fishery management was broad and could be obtained in a variety of ways—one size did not fit all. Similarly, we did not want the concept to be too vague. Thus we found it easier to use the “maintain ecosystem health and sustainability” standard by thinking in terms of management actions to avoid on the way to accomplishing the goal. Clearly, overfishing, ignoring bycatch, and damaging the habitat are not likely measures for achieving ecosystem health and sustainability.

Policies

To assess the application of ecosystem principles, the panel devised six policies that we thought would be used in ecosystem-based management. The extent to which management institutions applied these policies would help to show how their management went beyond the scope of effective fishery management.

Briefly stated, ecosystem-based fishery management policies include:

1. Change the burden of proof. We live in a world where humans are an important component of almost all ecosystems. Thus it is reasonable to assume that human activities will affect ecosystems. The *modus operandi* for fisheries management should change from the typical mode of restricting fishing activity only after it has demonstrated an unacceptable impact, to a mode of allowing only fishing activity that can be reasonably expected to operate without unacceptable effects.

2. Apply the precautionary approach. The precautionary approach is a key element of the United Nations Agreement for Straddling Stocks and Highly Migratory Species (United Nations 1996) and the Food and Agriculture Organization of the United Nations (FAO 1995) Code of Conduct for Responsible Fisheries. The United States is a signatory of both.

3. Purchase "insurance" against unforeseen, adverse ecosystem impacts. Even under the precautionary approach, there is a risk of unforeseen, adverse effects on ecosystems. Insurance can be used to mitigate these effects if and when they occur. Designation of marine reserves can provide insurance.

4. Learn from management experiences. Management actions and policies can be considered as experiments and should be based upon hypotheses about the ecosystem response. This requires close monitoring of results to determine to what extent the hypotheses are supported.

5. Make local incentives compatible with global goals. Human behavior is most easily changed by changing the local incentives to be consistent with broader social goals. The lack of consistency between local incentives and global goals is the root cause of many "social traps," including those in fisheries management (Costanza 1987). Changing incentives is complex and must be accomplished in culturally appropriate ways.

6. Promote participation, fairness, and equity in policy and management. Ecosystem approaches to management rely on the participation, understanding, and support of multiple constituencies. Policies that are developed and implemented with the full participation and consideration of all stakeholders, including the interests of future generations, are more likely to be fair and equitable and to be perceived as such.

Application in Fishery Management

Lacking the time and the resources to perform a systematic appraisal of how the panel's ecosystem principles are applied in current fishery management, we chose to conduct an overview based on presentations by fishery managers and scientists from the eight regions, on fishery management literature, and on the experience of panel members. After studying all of these materials, the panel concluded that the regional councils and NMFS already consider and apply some of the principles, goals, and policies. But they are not applied comprehensively or evenly across the regions or ecosystems under council and NMFS jurisdiction. This is not the result of these entities' intransigence toward adopting ecosystem-based management. Rather, they lack the clear mandate and resources from Congress to carry out such an approach. Further, the panel recognized that the concept of ecosystem-based management in fisheries is relatively new and that there are considerable gaps in knowledge and practice.

RECOMMENDATIONS

We strongly believe the key to an effective ecosystem approach is to fish more conservatively. The depressed condition of many U.S. stocks relates primarily to unsustainable levels of fishing effort, rather than to ecosystem effects. With few exceptions, fishery managers understand the levels of fishing effort required to produce sustainable yields, but are challenged by a highly politicized process to exceed those levels for short-term gains. Setting maximum sustainable yield and optimum yield conservatively, and respecting these conservative goals in the face of political and economic pressure is essential in any ecosystem approach. Fishery management plans for single species or species complexes should continue to be the basic tool of management for the foreseeable future. But management actions under FMPs alone are not sufficient to implement ecosystem-based management.

The panel has divided its fishery management and policy recommendations to Congress into two parts. First we recommend that a fisheries ecosystem plan (FEP) be prepared by each council to continuously guide management decisions. Second, we recommend immediate measures to start implementing the FEP concepts under current fishery management authority. The panel's recommendations for research derive from the information needs of the FEP.

The Fisheries Ecosystem Plan

Our primary recommendation is that each council (including the NMFS in the case of Atlantic highly migratory species) develop an FEP as a mechanism for incorporating ecosystem principles, goals, and policies into

the present fisheries management structure. The objectives of FEPs are to

- provide council members with a clear description and understanding of the fundamental physical, biological, and human/institutional context of ecosystems within which fisheries are managed;
- direct how that information should be used in the context of FEPs; and
- set policies by which management options would be developed and implemented.

Councils would develop FEPs for each major ecosystem under their jurisdictions. For example, the North Pacific Fishery Management Council might have two FEPs—one for the Bering Sea/Aleutian Islands and one for the Gulf of Alaska. Councils with overlapping ecosystems or with significant species migration across ecosystem boundaries would work together on a joint FEP. In the event of transnational ecosystems, international arrangements would be sought to implement an ecosystem approach.

The FEP should be used as a metric against which all fishery-specific FMPs are measured to determine whether or not management effectively incorporates the ecosystem principles, goals, and policies. The FEP should also contain regulations or management measures which would extend across individual FMPs. The FEP should serve as a nexus for existing FMPs and provide a context for considering council management actions with respect to all living marine resources, whether managed or not.

The FEPs must contain information about ecosystems that allows managers to make informed decisions, but the primary purpose of the plans is to prescribe how fisheries will be managed from an ecosystem perspective. Careful consideration must be given to the structure and required content of an FEP to balance the needs for plans to be both substantive and realistic. It is appropriate that NMFS lead a deliberative process (including a broad range of interests and expertise) to prepare guidelines for FEPs (analogous to the processes that have been used to prepare guidelines for implementing national standards under the MSFCMA). Preparation of such specific guidelines was beyond the scope of the panel's charter (NMFS 2000), but we did identify council actions that must be taken when guidelines are prepared, to be consistent with our recommendations.

Each FEP should:

1. Delineate the geographic extent of the ecosystem(s) within council authority, including characterization of the biological, chemical, and physical dynamics of those ecosystems, and "zone" the area for alternative uses.

The first step in using an ecosystem approach to management must be to identify and bound the ecosystem. Hydrography, bathymetry, productivity, and trophic struc-

ture must be considered, as well as how climate influences the physical, chemical, and biological oceanography of the ecosystem, and how, in turn, the food web structure and dynamics are affected. Transfers across ecosystem boundaries should be assessed.

Within each identified ecosystem, councils should use a zone-based management approach to designate geographic areas for prescribed uses. Such zones could include marine protected areas, areas particularly sensitive to gear impacts, and areas where fishing is known to negatively affect the trophic food web.

2. Develop a conceptual model of the food web.

For each targeted species, there should be a corresponding description of both predator and prey species at each life-history stage over time. FEPs can then address the anticipated effects of the allowed harvest on predator-prey dynamics.

3. Describe the habitat needs of different life-history stages for all plants and animals that represent the "significant food web" and how they are considered in conservation and management measures.

Essential fish habitat (EFH) for target and nontarget species at different life stages should be identified and described. Using habitat and other ecosystem information, councils should develop zone-based management regimes, whereby geographic areas within an ecosystem would be reserved for prescribed uses. FEPs should identify existing and potential gear alternatives that would alleviate gear-induced damage to EFH, as well as restrict gears which have adverse effects. Further, FEPs should evaluate the use of harvest refugia as a management tool to provide habitat for target and nontarget species.

4. Calculate total removals—including incidental mortality—and show how they relate to standing biomass, production, optimum yields, natural mortality, and trophic structure.

Total removals (i.e., reported landings, unreported landings, discards, and mortality to fish that come into contact with fishing gear but are not captured) should be incorporated into qualitative food web and quantitative stock assessment models. These models will allow managers to reduce uncertainty, monitor ecosystem health, and better predict the relative abundance of species affected by the harvest of target species.

5. Assess how uncertainty is characterized and what kind of buffers against uncertainty are included in conservation and management actions.

Given the variability associated with ecosystems, managers should be cognizant of the high likelihood of unanticipated outcomes. Management should acknowledge and account for this uncertainty by developing risk-averse management strategies that are flexible and adaptive.

6. Develop indices of ecosystem health as a target for management.

Ecosystem health refers to a balanced, integrated, adaptive community of organisms with a species composition, diversity, and functional organization that has evolved naturally. Provided that a healthy state can be determined or inferred, management should strive to generate and maintain such a state in a given ecosystem. Inherent in this management strategy would be specific goals for the ecosystem, including a description of unhealthy states to be avoided.

7. Describe available long-term monitoring data and how they are used.

Changes to the ecosystem cannot be determined without long-term monitoring of biological indices and climate. Long-term monitoring of chemical, physical, and biological characteristics will provide a better understanding of oceanic variability and how climate changes affect the abundance of commercially important species and their corresponding food webs.

8. Assess the ecological, human, and institutional elements of the ecosystem which most significantly affect fisheries, and are outside council/Department of Commerce authority. A strategy should be included to address those influences in order to achieve both FMP and FEP objectives.

Councils and the secretary of commerce have authority over a limited range of human, institutional, and natural components of a marine ecosystem. It is important to recognize the components of the ecosystem over which fisheries managers have no direct control, and to develop strategies to address them in concert with appropriate international, federal, and state agencies as well as tribes and local entities.

Implementing FEPs

Two general types of actions are required to implement FEPs in U.S. fishery management. The first type consists of short-term actions taken under existing authority. The second is a direct legislative mandate from Congress that might be developed as a part of reauthorization of the MSFCMA. Examples of these measures are elaborated below.

Short-Term Actions.

1. Encourage the councils to apply ecosystem principles, goals, and policies to ongoing activities.

Councils should begin to apply the ecosystem principles, goals, and policies to the conservation and management measures of existing and future FMPs. Three actions are particularly important:

A, Consider predator-prey interactions affected by fishing allowed under the FMP; B, consider bycatch taken during fishing operations and the effects of such removals on the species and the ecosystem as a whole, in terms of food web interactions and community

structure; and C, minimize impacts of fisheries operation on EFH.

Councils have received copies of the panel's report, but so far no council has taken significant action to formally adopt the approach. Most council and agency attention has been focused on implementing the Sustainable Fisheries Act and developing other instruments to bring fishery management into full environmental compliance.

2. Provide training for council members and staff.

To facilitate an ecosystem approach and to aid the development and implementation of FEPs, the NMFS should give all council members basic instruction in ecological principles. Further, training materials should be made available to the fishing industry, environmental organizations, and other interested parties. To date, only limited efforts have been made to educate councils about the nature of the panel's recommendations.

3. Prepare guidelines for FEPs.

The secretary of commerce should charge the NMFS and the councils with establishing guidelines for FEP development, including a regular amendment process. The NMFS and the councils should conduct a deliberative process similar to that for developing guidelines for the national standards to ensure that FEPs are realistic and adaptive. The NMFS has convened a workshop on incorporating ecosystem principles into stock assessments but, because of all its other responsibilities, has not made a systematic effort to further develop guidelines.

4. Develop demonstration FEPs.

While encouraging all councils to develop framework FEPs, the secretary of commerce should designate a council or councils to develop a demonstration FEP as a model to further advance the concept as spelled out by the panel. This will contribute a better empirical understanding of the management context and applicability of the recommendation. It can also facilitate more rapid implementation of full FEPs if required by Congress. The NOAA Chesapeake Bay office has taken the initiative to develop an FEP for Chesapeake Bay and convened a workshop in Solomons, Maryland, in July 2000. Other efforts are being made in academic institutions to advance the FEP concept, e.g., Field et al. (this volume).

5. Provide oversight to ensure the development of and compliance with FEPs.

To ensure the development of FEPs, the secretary of commerce should establish an oversight panel. Implicit in this action is the establishment of a timetable for developing a draft demonstration FEP and review.

Legislation. The panel recommends that Congress enact legislation requiring FEPs. In 2000 three bills in-

roduced into either the House or the Senate carried provisions to require FEPs in U.S. fishery management as part of MSFCMA reauthorization processes. One of the legislative approaches (that of Senator Snowe) is extremely close to the panel recommendations. Another (that of Representative Gilchrest) tracks the recommendations closely but makes the FEP mandatory, with a short time line for preparing the plans once legislation is enacted. The third bill (that of Senator Kerry) revises the recommendations somewhat, but in ways quite compatible with their intent. Although no action was taken by Congress on any of the measures, the fact that they all appear to embrace the recommendations of the panel does bode well for subsequent action.

Research

In its review of the application of ecosystem principles in U.S. fisheries management activities, the panel also found that the information required to develop and implement FEPs is limited. In order to provide the broader ecosystem information required to implement this approach, additional research is recommended. The panel identified three general areas of research that are essential for providing information to underpin ecosystem-based management. First, there is a need to increase understanding of the ecosystem effects of fishing. Fishing can affect target species, nontarget species, habitat, and marine ecosystems as a whole. Second, we must do a better job of monitoring trends and dynamics in marine ecosystems. This will require an expanded monitoring of broadscale ecosystem parameters and must be undertaken with the best available technology. Third, because many of today's fisheries problems stem from governance systems which create incentives that are incompatible with, or inimical to, ecosystem-based fishery management, alternate governance systems and approaches must be identified consistent with the scale and needs of fisheries management in an ecosystem context.

CONCLUSIONS

Under an ecosystem-based management system, U.S. fisheries are likely to be quite different from fisheries today. New management tools, including share-based systems, will be employed. Fisheries and gear types that significantly affect other ecosystem components may be modified or phased out, and other types of fisheries and gears may replace them. In many cases, fish stocks may have to be exploited at lower harvest levels than presently indicated in order to sustain other ecosystem compo-

nents. Some areas that are now fished may become reserves where harvests are restricted to protect a spawning stock or other sensitive life-history stages. The short-term consequences of such changes, which may be painful, must be balanced against future benefits in the form of sustainable fisheries for fishing communities and for the ecosystems on which they depend.

The next ten years are critical for the future of U.S. fisheries. Already, important changes are under way as a result of the SFA, and the next round of legislation/reauthorization of the MSFCMA should provide additional impetus for reform. Implementation of an ecosystem-based approach will take time, and there will be trials and errors. A great deal of education about this new approach will be required, and all involved must be prepared to learn. The two hardest changes in policy are likely to be shifting to the fishery the burden of proof to demonstrate that the ecosystem will not be damaged by fishing, and developing a truly precautionary approach to fishery management. The learning curve will be steep for all involved; society as a whole will be increasingly challenged to help define ecosystem health and the limits of acceptable change in marine ecosystems, while still allowing sustainable fishing practices.

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APPENDIX: NMFS ECOSYSTEM PRINCIPLES ADVISORY PANEL

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TOWARD A FISHERIES ECOSYSTEM PLAN FOR THE NORTHERN CALIFORNIA CURRENT

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We have witnessed changes in the landscape around us with the advent of technology evolved from the axe and the plow. We should expect equally profound ecological changes from modern, large-scale uses of the hook and the net. (EPAP 1999)

ABSTRACT

Recently the congressionally established Ecosystem Principles Advisory Panel issued a report on how best to amend single-species management. A major recommendation was that fisheries management councils develop a fisheries ecosystem plan (FEP) for every ecosystem under their jurisdiction. This document would be an umbrella document containing detailed information on the structure and function of the ecosystem under consideration. The U.S. portion of the northern California Current ecosystem (NCCE) may be an appropriate test case to develop some of the key elements of a draft FEP. Fishing pressure in the NCCE has been intense for decades, and the possibility of consequent large-scale ecosystem changes is large. Although fisheries science in this region has considerably advanced our understanding of the intricate linkages between fisheries production and large-scale oceanographic and atmospheric climate forcing, fisheries management efforts throughout the region may be insufficient for assessing the ecological impacts associated with fishing. We use Ecopath models to assess the state of the NCCE in the 1960s during a cool regime with low exploitation rates and high rates of zooplankton production, and also in the 1990s during a warm regime characterized by low productivity, declining stocks, and intense exploitation. We compile population parameters and diet data for 34 species/species assemblages for both time periods to generate a food web of basic trophic interactions. These models are in agreement with the general consensus that this system has been functioning at lower levels of productivity since the 1977 regime shift. More work is needed to understand the status of many NCCE populations, but stock assessments and fisheries data suggest that the observed fluctuations in many harvested populations may be rapid, highly variable, and increasingly undesirable.

INTRODUCTION

To date, most fishery management efforts in the United States continue to focus on regulatory mandates

contained in management plans based on species-specific stock assessments. The Magnuson Fishery Conservation and Management Act, which provides the legal authority for marine fisheries management, mandates that fisheries scientists and managers "prevent overfishing while achieving, on a continuing basis, the optimum yield from each fishery" (16 U.S.C. 1851). Although there is legal authority for taking into account how fishing activities affect fish habitat, this authority has generally not been used by managers, and the Magnuson Act contains no explicit direction on how managers should actively consider the indirect consequences of fishing on trophic dynamics or structure.¹

Recognizing the promise of an "ecosystem-based" approach to improving fisheries management, the U.S. Congress recently requested that the National Marine Fisheries Service (NMFS) convene a panel of experts, the Ecosystem Principles Advisory Panel (EPAP), to examine how best to build upon single-species management approaches. The EPAP's primary recommendation was that fishery management councils develop a fisheries ecosystem plan (FEP) for every ecosystem under their jurisdiction (EPAP 1999). An FEP is envisioned as an umbrella document containing detailed information on the structure and function of the ecosystem under consideration (e.g., a conceptual model of the food web and other ecosystem components, total removals from fishing, and assessments of the human elements of the ecosystem that most significantly affect fisheries). The FEPs would be intended to increase managers' and stakeholders' awareness of how their decisions affect the ecosystem. As such, FEPs would be the next major step in translating today's directed management efforts into more holistic approaches.

Our efforts have focused on using the U.S. portion of the northern California Current ecosystem (NCCE), which includes the heavily fished shelf and slope ecosys-

¹The extent to which the Magnuson Act explicitly mandates the consideration of ecosystem aspects could be arguable, as there is no mention of ecosystem considerations in the National Standards or in the FMP requirements. However, some authority is inferred in the definitions section of the act with regard to the word *optimum* with respect to yield from a fishery (Section 104-297 of 16 U.S.C. 1802), where it is suggested that optimum yield "means the amount of fish which will provide the greatest overall benefit to the Nation, particularly with respect to food production and recreational opportunities, and taking into account the protection of marine ecosystems."

tems between Cape Mendocino, California, and the northern tip of Vancouver Island, as a test case to develop what we believe to be some of the key elements of a draft FEP. Fisheries resources in the NCCE have been subjected to intensive fishing pressure for a protracted period. The abundance of coastal pelagic species such as sardine, anchovy, and herring has varied substantially over past decades, most likely in direct association with different modes of climate forcing. Precipitous declines in several stocks of Pacific rockfish (*Sebastes* spp.) and some roundfish have occurred over the last 20 years, and are evident in the corresponding declines of commercial landings (Ralston 1998). Similarly, many salmon fisheries of the NCCE, in particular ocean fisheries, have been in decline since the late 1970s. These declines are generally attributed to a combination of unfavorable ocean conditions (Hare et al. 1999), spawning and rearing habitat degradation and loss, and overfishing (NRC 1996). Juvenile salmon, a staple in the diet of many higher-trophic-level species, have been particularly affected by habitat loss and interdecadal variations in climate (Mantua et al. 1997; Hare et al. 1999); the recruitment of rockfish, the juveniles of which are also a staple in the diet of many larger predators in this system, has similarly been greatly reduced in recent decades (MacCall 2000).

The complex and fragmented design of interacting human and institutional elements hinders the transition to more holistic management efforts in this ecosystem. Under an ecosystem-based approach, management actions would be designed and monitored through an adaptive management approach (Ludwig et al. 1993), and management institutions should be designed so that resource ecology and institutional ecology overlap in a complementary manner. All of these issues of governance are particularly true in the NCCE, where numerous state, federal, and tribal institutions often seem to have different responsibilities with regard to the management of fishery resources. Of particular concern is the challenge of incorporating a longer time and broader spatial and biological view into this management arena. Thus the northern California Current may provide an opportunity to explore efforts for surmounting the impediments to sustainable and rational management of living marine resources.

WHY ECOSYSTEM-BASED MANAGEMENT?

In many fisheries it has become increasingly obvious that the ecological consequences of fishing are substantially greater and more complex than the biomass reductions of target species. These consequences may include but are not limited to mortality of nontarget species, alteration of benthic habitats and bottom topography, changes in age and size structure of fished (both target

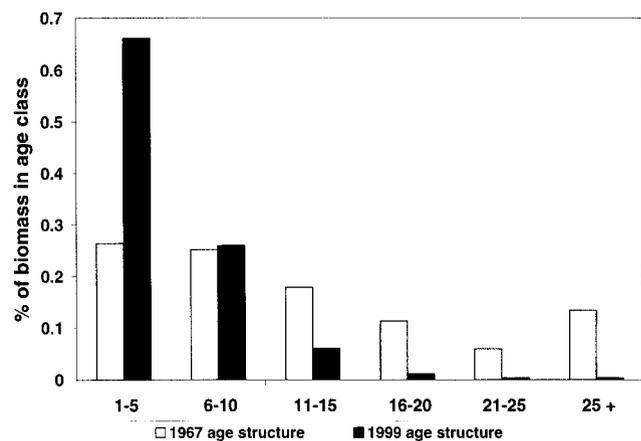


Figure 1. Changes in the age structure of the northern canary rockfish population (based on stock assessment data). Graph shows the percentage of population biomass in five-year groupings of age classes between 1967 and 1999, illustrating the shift in population biomass to younger, smaller individuals. During this same period the total population has been fished down to approximately 10% of its unfished population biomass.

and nontarget) populations, changes in sex ratios of targeted populations, and changes in the genetic structure of fished populations (Botsford et al. 1997; NRC 1999).

As one simple example, figure 1, based on the stock assessment by Crone et al. (1999), shows how the age structure of the canary rockfish population has changed over the last three decades. This figure shows an extreme case of the truncation of the age distribution of this long-lived species. Recruitment of canary rockfish has been extremely low over the last two decades, and the large proportion of young individuals does not reflect increased recruitment, but rather removals of a substantial fraction of older individuals.

In addition to population impacts, structural changes to trophic webs have been described for numerous heavily fished ecosystems (Parsons 1993; Apollonio 1994; Fogarty and Murawski 1998; Pauly, Christensen et al. 1998). Furthermore, interannual and interdecadal climate shifts affect the productivity of marine populations, with dramatic effects on fisheries (Mantua et al. 1997; Anderson and Piatt 1999; Hare and Mantua 2000). The effects on marine ecosystems as a consequence of fishing activities, notably as direct effects of fishing gear on benthic habitats, are poorly understood in most systems, but have been shown to be substantial where evaluated (Auster et al. 1996; Engel and Kvitek 1998).

Figure 2 is a simplistic representation of how traditional approaches to fisheries management, which focus primarily on interactions between commercially important populations and fishing activities, could be broadened to include basic interactions between commercial and noncommercial species, the effects of fishing activities on habitat, and the large-scale impacts of climate forcing on ecosystem productivity and structure.

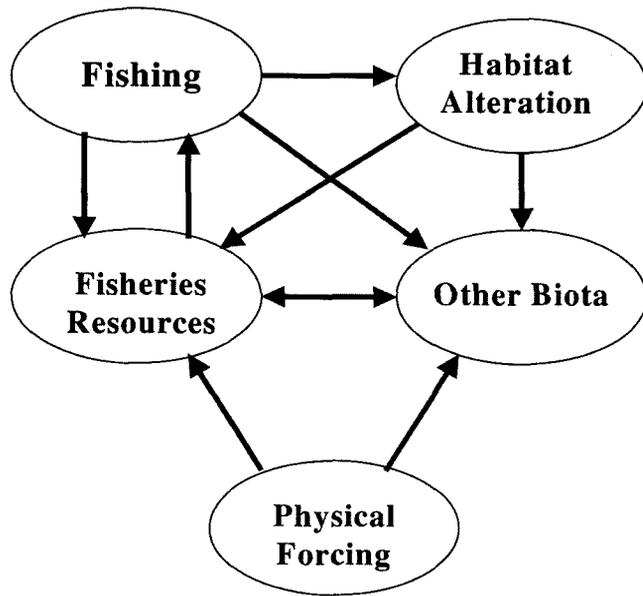


Figure 2. A conceptual outline for incorporating ecosystem considerations into fisheries management.

It is widely recognized that an ecosystem approach to fisheries management will have different meanings for different people. As with much environmental legislation, a mandated ecosystem-based approach will invite controversy about its implementation, regardless of the definitions put into the law. The discussion on what an ecosystem-based approach might mean to managers is broad and often tortuous, yet some mention of key views is worthwhile. For example, Grumbine (1994) suggests that managing for ecological integrity would mean that commodity extraction should be relegated to an ancillary goal. As the EPAP report (1999) points out, when fishing is examined from an ecosystem context the rationale for surplus production is unclear; before the advent of fisheries all production was recycled within ecosystems. Other stated consequences of fishing include inducing ecological changes among competitors, predators, and prey, and such changes could imply future levels of surplus production that approach zero for some populations well into the foreseeable future. This is in direct conflict with the assertion by some that the adoption of an ecosystem-based approach should lead to healthier and more dependable fisheries. For example, the NRC Council on Sustainable Fisheries Report (NRC 1999) suggests that the goals of an ecosystem-based approach are to “rebuild and sustain populations, species, biological communities and marine ecosystems at high levels of productivity and biological diversity, so as not to jeopardize a wide range of goods and services from marine ecosystems, while providing food, revenue and recreation for humans.”

Like so many policy and management approaches, the purported objective in the NRC report is to maximize

many variables at once, thereby implying that all of the objectives are mutually compatible. This approach, like that of traditional fisheries management, continues on the assumption that fisheries can safely remove surplus production without consequences to the ecosystem; as implied by the conclusion that although adaptation of such an approach will likely cause short-term economic losses and impacts to communities, the ultimate outcomes should not include decreased yield, since rebuilt populations should increase sustainable yield (NRC 1999).

These assumptions are difficult to justify given the current poor state of knowledge about the aforementioned ecological consequences of fishing on marine ecosystems, revelations that many long-lived species have considerably lower rates of production than previously thought and may take many decades to recover, and our inability to clearly define what might or might not constitute a “healthy” marine ecosystem. Moreover, there should be little reason to use higher potential yields as a selling point of ecosystem management, as the solution to a stock’s inability to produce some level of sustainable yield would (and under the Sustainable Fisheries Act, legally should) ostensibly be reached through the adoption of quota reductions and stock rebuilding plans under a single-species approach. In the future, as policymakers and resource managers struggle to consider what ecosystem management is, perhaps it will be worthwhile to step back and consider what it is not.

One potential outcome of implementing an ecosystem-based approach could be reduced stability or predictability in future fishery yields. A reduction in predictability does not necessarily imply that most current yields are stable, but rather that the pursuit of stability for economic and allocation purposes may be in conflict with the notion of adaptive management of ecological resources. Holling and Meffe (1996) argue that the pursuit of stability is part of the explanation for why many resource management efforts have failed, because the objectives of many such efforts have been to reduce the natural bounds of variation in ecological systems in order to make them more predictable and more reliable for extractive needs. Holling and Meffe argue that the key to natural resource management, whether it be single-species or ecosystem management, is to retain critical types and ranges of natural variation in ecosystems, and to facilitate existing processes and variabilities rather than attempting to alter or control them.

Perhaps one example of such an approach can be observed in the recently approved fishery management plan for coastal pelagic species (PFMC 1998). The plan was based on the premise that the theoretical definition of maximum sustainable yield (MSY) as a constant level of catch should not be applied in fisheries for coastal pelagic species such as sardine, anchovy, and mackerel because

of the high sensitivity of the productivity of these stocks to changes in environmental conditions. Instead, management is based on the application of a baseline "cut-off" population biomass, below which directed harvests are not allowed, and above which allowable landings are based on a fraction of the available biomass above the cutoff level. This approach allows for high harvest rates during favorable environmental conditions but forces fishing mortality to zero if the stock declines to a baseline biomass.

Apollonio (1994) suggests that in marine ecosystems, the ecological role of fishing is comparable to the role of apex predators. It follows that, analogous to the way biological feedback mechanisms underlie natural predator-prey relationships, appropriate feedback mechanisms between vessels and target species should exist to keep the system in balance. In order for fishing to be ecologically sustainable, Apollonio argues, the ecological impacts of fishing should be similar to the natural impacts of apex predators. This may imply that during unproductive years, decades, or even longer periods, the yield of many species, indeed of many ecosystems, may be unsustainable from the perspective of stock, species, or system productivity.

The Pacific Council's Coastal Pelagic Species FMP is one step toward the application of this principle, yet in practice these balancing mechanisms are scarce because of external subsidies, which have the effect of maintaining fisheries that might be otherwise unprofitable. Instead, fleet buildups continue far beyond what might be sustainable as stocks are fished down to (and often beyond) the estimated size that produces the maximum sustainable yield. The existence of strong incentives for vessels to switch rapidly from one fishery to another when catches decline, and the ability for effort to shift massively over short time periods would suggest that the feedbacks that might exist in a more typical predator/prey system are substantially diminished.

For the northern California Current, our initial work has focused on preliminary attempts to address three of the eight key minimum actions envisioned in the EPAP report as elements of demonstration fishery ecosystem plans. These include a characterization of biological dynamics of the ecosystem, development of a conceptual model of the food web, and the estimation of total removals and how those relate to standing biomass, production, and trophic structure. A summary of our early efforts to address these elements makes up the remainder of this paper.

The remaining five key elements of FEPs as envisioned by the EPAP panel are certainly no less crucial. They include descriptions of the habitat needs of different life-history stages for all plants and animals that represent the "significant food web" and how they are

considered in conservation and management measures; an assessment of how uncertainty is characterized and what types of buffers are included in management actions; the development of indices of ecosystem health as targets for management; descriptions of long-term monitoring data and how they are used; and an assessment of the ecological, human, and institutional elements of the ecosystem that most significantly affect fisheries and are outside of Council/Department of Commerce authority (see Fluharty and Cyr, this volume, for greater detail). For all of these actions, the FEP process would provide an opportunity to refine, integrate, and further develop the substantial efforts that have already been made by government and academic workers.

THE NORTHERN CALIFORNIA CURRENT ECOSYSTEM

The continental margin of North America off the coasts of northern California, Oregon, Washington, and southern British Columbia is a productive coastal upwelling region that has long supported commercial harvest of a variety of marine resources. The entire California Current ecosystem (CCE) is an "open" system, meaning that it is a transition environment between subarctic and subtropical water masses and the freshwater systems that enter the ocean along its landward boundary (Hickey 1989).

This region is also an ecotone comprising a small number of endemic coastal species and a larger mixture of subarctic and subtropical species, many near the periphery of their distributional range (Bottom et al. 1993). The northern half of the CCE, the region of coastal ocean between Cape Mendocino, California, and the northern tip of Vancouver Island, B.C., is described as a zoogeographic transition between Californian and Aleutian biological provinces. We refer to this region as the northern California Current ecosystem, and presume that this system may be an appropriate ecological unit for regional management as the focus of this paper.

A growing body of research has shown that during the twentieth century, both El Niño-Southern Oscillation (ENSO) and Pacific Decadal Oscillation (PDO) processes had major impacts on the organization and dynamics of marine ecosystems of the NE Pacific Ocean and, as a result, on fisheries operating within those ecosystems (e.g., Wooster and Fluharty 1985; Francis et al. 1998; McGowan et al. 1998; Anderson and Piatt 1999). Because the effects of climate are so pervasive in the NCCE, as a first step to ecosystem reconstruction it is essential to understand past patterns of climate as they may have affected the NCCE. As an example of how past climate patterns have influenced the NCCE, we will briefly examine information about the presence of Pacific sardine in the region over the last two centuries.

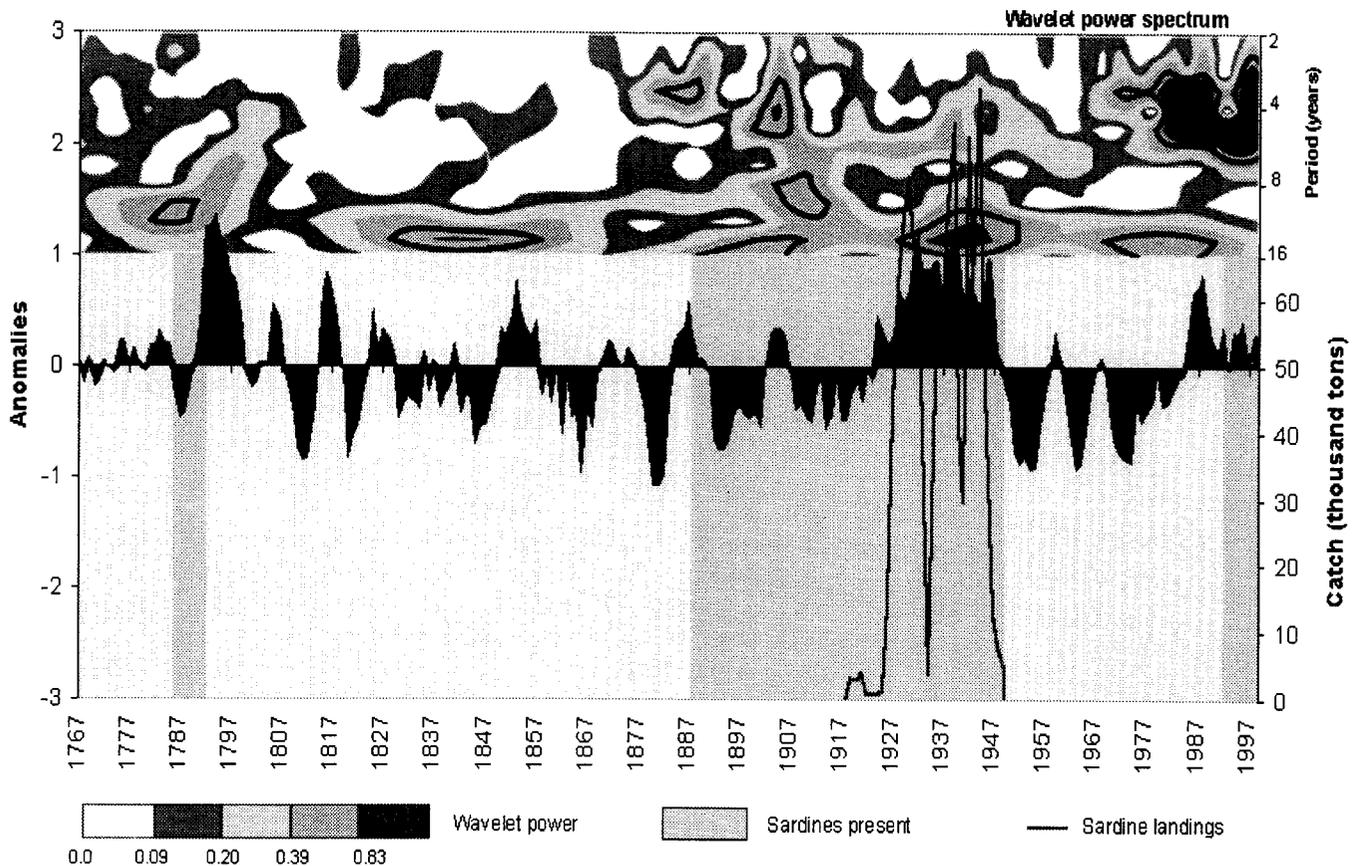


Figure 3. Pacific Northwest sardine occurrences charted against reconstructed winter PDO and ENSO wavelet power spectrum. (See footnote 1 for a summary of historical records of sardine presence/absence in the Pacific Northwest.)

Figure 3 is a composite that explores possible relationships between climatic influences and the presence and absence of sardines in the NCCE. Shaded areas indicate periods of sardine presence; solid lines indicate commercial landings in the Pacific Northwest. This information is plotted against a tree-ring reconstruction of the PDO time series (Dell’Arciprete et al. 1998) and a wavelet analysis of the ENSO cycle (top panel) as reconstructed by Mann et al. (1999). The wavelet analy-

sis provides a graphic representation of the intensity, or magnitude, of climate variability at various frequencies (see Torrence and Compo 1998). Darker shades in the upper panel indicate more intense ENSO periods.

Figure 3 suggests that each range expansion of sardines documented since the latter part of the eighteenth century occurred during periods of increased North Pacific climatic activity.² The first period of increased activity occurred in the late 1700s, when sardines were

²It appears that three major northward expansions in the range of sardines have occurred since the late 1700s. During the first two, sardines were abundant enough to support substantial fisheries that persisted for a number of years as far north as Puget Sound and Vancouver Island. Between 1786 and 1792 a number of accounts, including those of trained naturalists, described the native fisheries for sardines along the Pacific Northwest coast; John Meares (1791) described how “In the Spring, the herrings as well as the sardines frequent the coast in vast shoals.... The sardine resembles that of Portugal, and is very delicious; they are taken here by the people in prodigious quantities.” By the beginning of the 19th century, however, sardines were no longer being noted in the journals of explorers, naturalists, or traders, despite more extensive exploration in the Pacific Northwest region following the Lewis and Clark expedition.

Apparently sardines did not return to the Pacific Northwest until the late 1880s. Extensive scientific investigations of fisheries resources—including those conducted by the Wilkes expedition in 1841 (Wilkes 1884), the Pacific railroad surveys of 1853–57 (Suckley 1860), and the investigations of the U.S. Fish Commission in 1880–81 (Goode 1884)—failed to locate sardines in Pacific Northwest waters. The U.S. Fish Commission reported in 1884 that sardines ranged from Chile to Cape Mendocino, California. By 1888–89, however, this range had expanded to encompass Puget Sound. Sardines were found in Puget Sound waters during “the warmer part of the season, and are taken with herring and other species for market” (Collins 1892). Landings of fresh sardines in 1888 were reported to be 60,000 lbs. By 1895 sardines were occurring in “large numbers” in Puget Sound (Jordan 1895), and in 1902 were described as “abundant” (Kershaw 1902). The first official records of sardines captured in Canadian waters did not appear until January 1900, when two specimens were collected in the Strait of Georgia near Nanaimo (Clemens and Wilby 1961). Concurrent with the development of the California sardine fishery in the 1920s, a lucrative fishery for sardines began in British Columbia in 1917–18 and lasted until 1948–49, when stocks once again disappeared (Schweigert 1988).

Sardines were again observed in the waters north of Cape Mendocino in the 1980s (Emmett and Brodeur 2000) and returned to the Pacific Northwest and British Columbia in 1992 (Hargreaves et al. 1994), though not in sufficient quantities to warrant a resumption of large-scale commercial fisheries. The return may also have been short-lived. In 1998 and 1999 there was a series of massive die-offs of sardines along northern sections of Vancouver Island. These mass deaths coincided with the 1998–99 La Niña that caused sharp declines in coastal ocean temperatures (Drouin 1999).

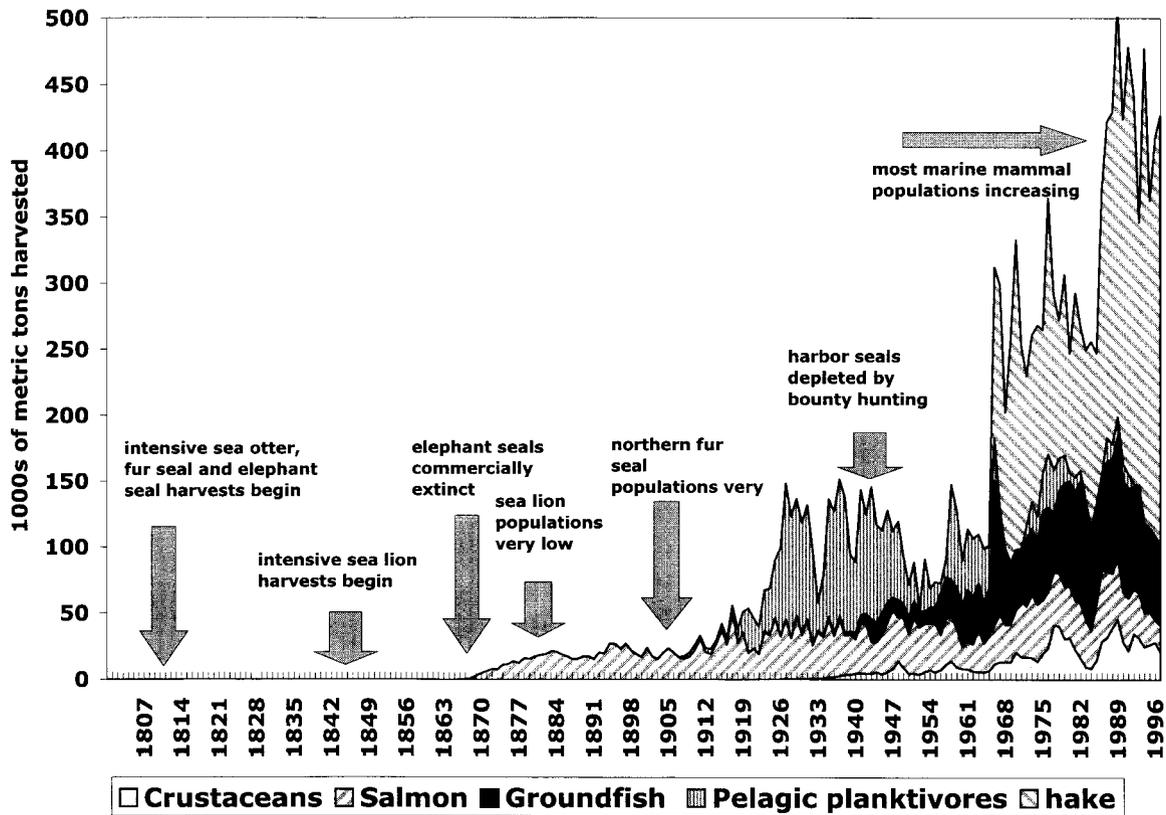


Figure 4. A summary of major removals by fisheries from the northern California Current ecosystem over the last two centuries.

apparently already in an expansion mode, the PDO was nearing a substantial peak, and ENSO activity may have been more intense and frequent than normal. It is unclear exactly when the sardines disappeared from Pacific Northwest waters during this period, but historical records suggest that they were no longer present by the early 1800s. Similarly, the expansion of the sardine population starting around 1880 coincided with increased power in both the ENSO signal and the magnitude of the PDO. Finally, the return of sardines to the British Columbia coast in the 1990s coincided with a general expansion of the coastal population, starting with the major climate shift of the late 1970s and the record El Niño activity of the 1980s and 1990s.

Sardines may epitomize the nature of change in key species in this system; their presence implies a different ecosystem state than during periods of their absence. This subsequently implies that key flows of energy and biomass in the system changed substantially prior to human intervention. Smith (1978) inferred changes of even greater magnitude in the abundance of Pacific hake in the California Current based on the scale record of Soutar and Isaacs (1974), which suggested that the abundance of hake (although these scales probably represent juvenile hake) at the turn of the twentieth century may have been as much as an order of magnitude greater than

current levels. These observations illustrate that pronounced changes of boom and bust in the natural cycles of migratory coastal pelagic species such as sardines and hake imply massive changes in primary and secondary production within the NCCE. This in turn suggests that the ecosystem was structured very differently in previous centuries than it is now.

FISHERIES DEVELOPMENT IN THE NCCE

Fishing pressure in the NCCE has been intense for decades and has effected consequent large-scale changes in the relative abundance of many key populations. Knowledge of NCCE structure and dynamics comes primarily from stock assessments, fisheries and food habits data, and oceanographic records. These sources mostly cover recent decades, and indicate high levels of physical and biological variability on broad spatial and temporal scales.

Catch statistics provide perhaps the most complete record of population trends, and indicate that rapid and possibly undesirable changes are occurring in NCCE structure. Figure 4 presents a partial accounting of catch data and major biological removals over the last two centuries, illustrating both the magnitude of removals and the sequential nature of the development of the major fisheries in the region. This figure shows that although

industrial-scale fishing pressure in the NCCE has been intense for only decades, various ecosystem components have been substantially exploited for at least two centuries.³

The first species to be the subject of major commercial exploitation were marine mammals. Fisheries for sea otters, fur seals, sea lions, and elephant seals grew to support enormous commercial harvests in the early and mid-1800s. Although few of these populations actively breed in the NCCE, all spend at least some of their time in Pacific Northwest coastal waters, and many are significant seasonal predators in the region. Estimates of actual take of most of these animals are difficult to derive: some estimates of otter and fur seal removals exist in fur trade records, but the number of elephant seals and sea lions taken for oil and meat can be only coarsely assessed.

Scammon (1874) suggested that hundreds of thousands of elephant seals must have been taken in the early part of the nineteenth century, and the species was commercially extinct by the 1870s. Specimen and museum collectors continued to take elephant seals even as the population was on the verge of extinction (Stewart et al. 1994).

Sea lions were originally taken for meat to supply the early hunters of sea otter along the California and Pacific Northwest coastline, and continued to be killed both as potential competitors for commercial fish as well as for their trimmings (the testes and penises of breeding bulls) following commercial depletion in the early twentieth century (Bonnot 1928).

Fishermen and bounty hunters along the U.S. and Canadian coastlines targeted harbor seals until the 1960s (Bonnot 1928; Newby⁴). Gray, humpback, sperm, and other whales were targeted for well over a century throughout the northeast Pacific. Such removals kept most pinniped and cetacean populations at low to moderate levels until the middle of the twentieth century, and only in the last several decades have populations of many marine mammals increased to substantial numbers.

Although many species of fish and shellfish throughout the NCCE have been harvested by native peoples

for millennia, some at rates that may have approached later commercial levels (Yoshiyama et al. 1998), large-scale commercial harvests of fish in the region generally did not begin until many marine mammal populations had been substantially depleted. The salmon fisheries were among the first to develop: the first salmon cannery was opened in 1864 along the Sacramento River, but was soon moved to the much more productive Columbia River. By 1885, salmon catches in the Columbia alone topped 40 million pounds, and salmon fisheries had expanded to nearly every major watershed in the Pacific Northwest (Cobb 1930). Salmon fisheries continued to dominate the region, even as the soon-to-be legendary California sardine fishery was initiated in the early twentieth century.

Total coastwide sardine landings would reach over 700,000 metric tons (t) per year. Although the vast majority of sardine landings were made in the southern part of their range, up to 80,000 t a year were caught in the summer fisheries of the northern California Current between the 1920s and 1940s. When this fishery began to collapse in the 1940s, it did so from north to south, and it has long been suspected that changes in marine conditions played a role in this population decline (Ueber and MacCall 1992). In British Columbia, substantial herring fisheries had developed during the period of the sardine fishery, and grew rapidly following the sardines' departure from northern waters (Waddell and Ware 1995) while anchovy and mackerel populations underwent substantial (and perhaps sequential) fluctuations in the southern part of the sardines' former range (MacCall 1996). As the sardine population has increased over the last two decades, the fishery has also undergone a resurgence, with sardines once more being fished in commercial quantities between Baja California and British Columbia.

Pacific halibut was the first of the groundfish species to be targeted by commercial fisheries, although flatfish, lingcod, rockfish, and sablefish were all supporting substantial fisheries throughout the NCCE by 1900. Total landings of all groundfish grew gradually throughout the twentieth century, approaching 20,000 t per year in the early 1960s. During the mid-1960s the Soviet Union (and several other nations) began fishing for hake and rockfish in the coastal waters of Oregon, Washington, and British Columbia, and coastwide landings quickly reached several hundred thousand metric tons per year (primarily hake). As a result of the declarations of 200-mile fishing zones by both the United States and Canada in the late 1970s, these foreign fisheries were phased out as domestic fleets developed, and overall landings continued to grow as the fleets greatly exceeded the capacity needed to harvest the resource (PFMC 1993). Following the rapid development of domestic fisheries, it was found that many of these stocks were consider-

³Data are incomplete, and from a variety of sources; salmon landings since 1911 were compiled by Hare et al. (1999), prior to 1911 are inferred from canned salmon production described by Cobb (1930). Pelagic planktivores (sardine, anchovy, herring, smelt, and shad) data were taken primarily from PFMC 1998, except for herring data taken from Waddell and Ware 1995 and very early landings from Sette and Fiedler 1928. Early groundfish and crustacean fishery data were also taken from Sette and Fiedler 1928, with later data from U.S. Bureau of Fisheries Statistical Digests. Groundfish and hake data between 1954 and 1980 were taken from Lynde 1986 and more recently from the Pacific Fishery Management Council (PFMC 1999) and Waddell and Ware 1995. Currently missing are Canadian data for groundfish landings prior to 1920 and all Canadian crustacean fisheries; errors are possible from other data sources, and not all estimates include unreported landings or estimates of discards, and thus should be considered minimum estimates of total mortality.

⁴Newby, T. C. Changes in the Washington state harbor seal population, 1942-1972. Unpubl. Rep.

ably less productive than originally thought. Subsequently, allowable landings of many groundfish species have been greatly curtailed in recent years, and recovery plans for depleted stocks are likely to limit effort for less-depleted stocks in the near future.

Crustacean fisheries also developed early in the Pacific Northwest, particularly fisheries for Dungeness crab and pandalid shrimp. For at least a century, landings of these populations appear to have fluctuated widely over relatively short periods of time. Evidence indicates that these fluctuations represent actual population swings, and recent research suggests that Dungeness crab dynamics respond to both internal population feedback, and large-scale environmental forcing (Higgins et al. 1997). It follows that such extreme population variability may be a response to a combination of anthropogenic influences (e.g., fishing, habitat degradation) and fluctuating oceanographic conditions.

Additionally, Hannah and Jones (1991) document an apparent change in the age structure of pink shrimp (*Pandalus jordani*), which they believe is at least partially attributable to fishing. The pink shrimp is a sequential hermaphrodite in which age-1 shrimp are typically male and turn female as they reach age 2 (few, if any, of this species live beyond age 3). Hannah and Jones's work documented a shift in the age structure of landed shrimp to a substantially greater percentage of age-1 shrimp and fewer age-2 and -3 shrimp. These changes were accompanied by an increased percentage of shrimp maturing directly into females at age 1.

To summarize, it is clear that major shifts in the biomass, productivity, and life-history characteristics of key trophic components have occurred in response to both human activities and environmental variability. Figures 3 and 4 are intended to scale the importance of considering the long-term effects of both climate and human disturbance, in order to develop a sense of history for what little we might know about the nature of past population changes in this ecosystem. These population shifts include volatile increases and decreases (crustacean populations); predictable large-scale spatial migrations (pelagics such as hake and sardine as well as many seabird and marine mammal populations); periodic species range expansions and contractions (sardine); changes in age structure of harvested populations (groundfish and shrimp); and recent steady biomass declines (many groundfish and salmonids).

These dynamic species assemblages and interactions define the trophic structure of the northern California Current, a structure that has changed substantially over time and space. Furthermore, the large-scale physical and biological properties of the NCCE (e.g., temperature and flow patterns, primary and secondary production) also vary greatly over time and space with

atmospheric forcing. Meine (1999) suggests that the "development of an historic sensibility ought to be considered fundamental to conservation biology"; we would argue that such a sensibility should be an integral part of fisheries biology and management as well, and is relevant in the context of both climatic and anthropogenic forcing mechanisms.

Although much more could be known about the trophic structure of the NCCE, it is clear that many species assemblages (and their ensuing interactions) are complicated and highly dynamic (Brodeur and Pearcy 1992). Thus, it may be that static fisheries models are not adequate for governing dynamic trophic systems, yet tangible objectives for ecosystem-level management initiatives remain ill-defined. If ecosystem-based approaches to fishery management are to be mandated by law or otherwise implemented, a major question will be how, if at all, managers might be able to ultimately incorporate insights and results of climate, trophic, dynamic, or other ecosystem models into management or policy objectives.

ECOLOGICAL MODELING OF THE NCCE

One opportunity for evaluating both the nature and the scale of such trophic interactions is to use ecological modeling. As a starting point, our efforts have focused on quantitatively defining NCCE trophic structure, using available information to explore the productivity of key populations in this region and evaluate how historical removals relate to standing biomass, production, and trophic structure. So far, we have centered on the initiation of an Ecopath modeling project designed to amass critical data on abundance, food habits, and other trophic factors. Future objectives include using dynamic simulations to incorporate modes of environmental forcing into dynamic simulations.

The intent of the discussion here is to explore the potential applications of one type of ecological model as a tool for describing the interacting effects of climate and trophic assemblages and deriving insights which could ultimately be useful for managers. With regard to the utility and application of multispecies or ecosystem models in particular, Hollowed et al. (2000) provide a comprehensive review of the most commonly used methods and their potential utility for measuring fishing impacts on marine ecosystems.

Ecopath was originally designed by Polovina (1984) and evolved into a software application, including a dynamic version called Ecosim, by workers at the University of British Columbia (Christensen and Pauly 1992; Walters et al. 1997). Essentially, Ecopath is a steady-state model that emphasizes natural rates of growth and consumption of marine populations. Given adequate data from fish bioenergetics models or diet composition studies, it provides a framework for summarizing information over

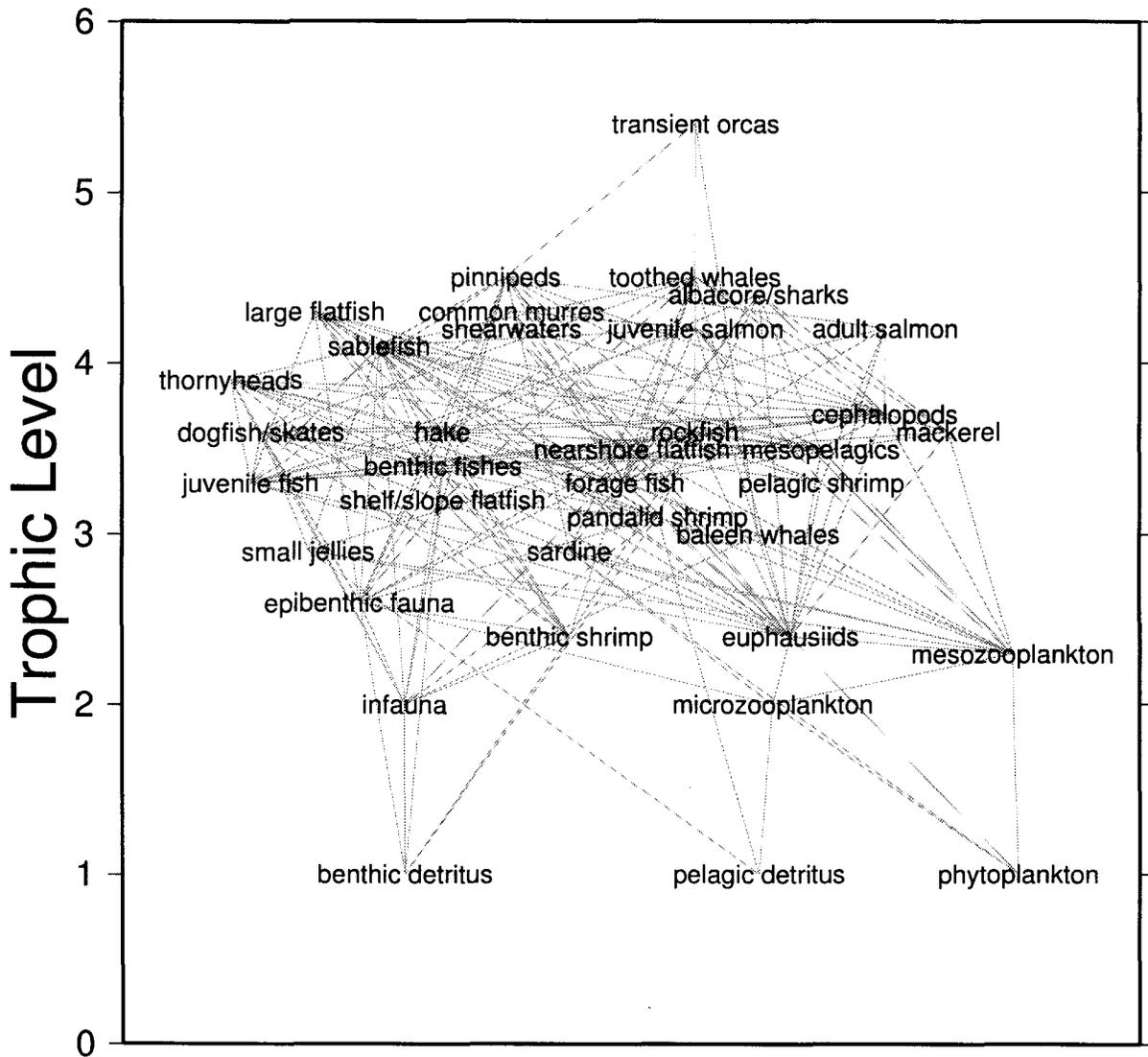


Figure 5. A model of the basic trophic components of the northern California Current food web. Despite massive aggregations of species and species assemblages, the picture illustrates the complexity of trophic interactions and the multitude of pathways for energy in this ecosystem.

trophic levels, emphasizing natural rates of growth and consumption of marine populations. This allows small-scale studies or models to be viewed in a common currency, in the context of the ecosystem as a whole. While the equilibrium assumptions of the Ecopath model do not allow for the determination of “true” biomasses or rates in a changing system, the modeler may use the software’s bookkeeping to examine the basic trophic processes; for example, to learn whether a predator or fishery may be consuming more forage than is hypothesized to be available, and thus if its existence is putting pressure on other ecosystem components. The assumption is that over an appropriate period of time (say a decade or a regime) a mass-balance model can be generated to represent the basic trophic interactions between major ecosystem components.

Although the stochastic nature of most (if not all) populations and population parameters would suggest that a range of values would better explain seasonal and interannual changes, the static approach is useful from the standpoint of generating a “snapshot” of some mean state(s) of the ecosystem under different time periods or circumstances. The quick examination of many components of the system essentially extends the concept of maximum sustainable yield to multiple interacting species, suggesting a management framework for examining the consequences of altering species abundance and species assemblages.

It must be stated at the outset that these models rely heavily on “back-of-the-envelope” calculations—stable, oversimplified trophic webs—and thus cannot reliably model sudden ecosystem shifts to new states. Yet this

generality and overstability may be their greatest recommendation. These models' potential may lie in developing metrics (e.g., the amount of primary production removed by fishing) relating measurable ecosystem quantities to levels of risk incurred by exploitation. At this time and despite great effort, measurable and meaningful metrics of ecosystem health, stability, and resilience have been elusive (Murawski 2000). Thus as a tool for developing management rules of thumb for avoiding ecological catastrophes, the comparison of simple, stable, pre- and postmanipulation equilibria or functional models with historic records of change in exploited ecosystems warrants further evaluation.

We have used preliminary Ecopath models to compare the state of the NCCE between the 1960s—a cool regime characterized by low exploitation rates and high rates of zooplankton production—and the 1990s—a warm regime characterized by low productivity, declining stocks, and intensively regulated fisheries following several decades of intensive exploitation. Population parameters and diet data for some 34 species or species assemblages were compiled or estimated for both time periods to generate a food web of basic trophic interactions (fig. 5).

The data used to estimate the parameters of this model come from a wide range of sources, including stock assessments, published literature, grey literature, and in many instances general review papers of basic population parameters. Model documentation and descriptions of data and data sources are available in Field and Francis.⁵ The challenges in compiling adequate data to parameterize the model inevitably suggest suspect results; because of the paucity of information regarding the dominant planktonic and nektonic populations in this region, some gross estimation and generalization is unavoidable. Nevertheless, we believe such models are extremely useful both for visualizing the nature of the system being managed and beginning to understand how major changes in species abundance or productivity might reverberate up or down through the food web.

Figures 6 and 7 show greatly simplified versions of trophic flow diagrams and energy pathways through the NCCE as modeled in the early 1960s and 1990s, and generated by aggregating the parameters for the 34 species and species assemblages shown in figure 5. The size of the boxes (if they were to be viewed in three dimensions) would be proportional to the log of estimates of average annual biomass (B) in the different assemblages. The average estimated production in the assemblages is given as P and consumption is given as Q. For lower trophic levels (in which annual production is the key param-

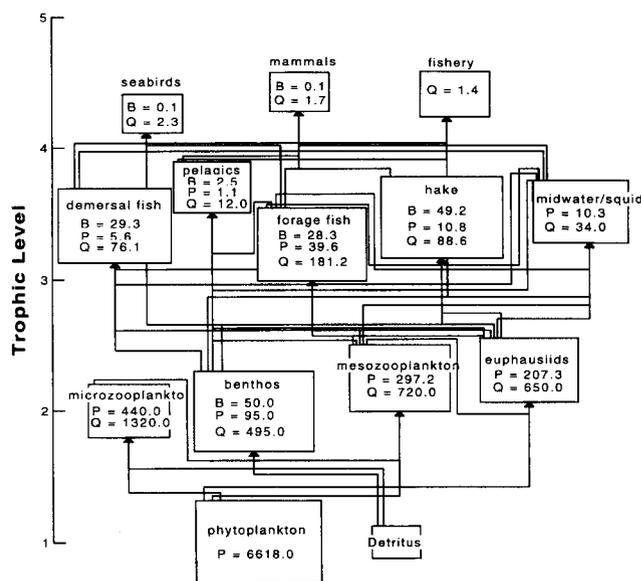


Figure 6. Simplified mass balance models of aggregated ecosystem components and major trophic flows in the northern California Current during the early 1960s. Units are wet weights of biomass (grams/square meter).

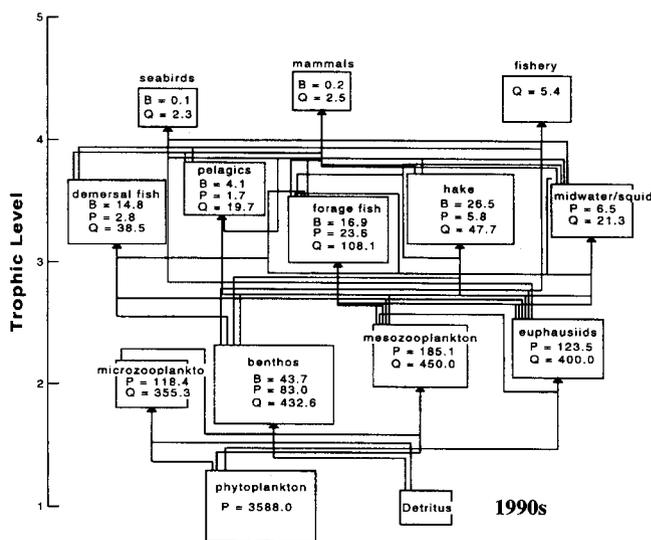


Figure 7. Simplified mass balance models of aggregated ecosystem components and major trophic flows in the northern California Current during the mid-1990s. Units are wet weights of biomass (grams/square meter).

ter) these estimates are based on a top-down estimate of consumption requirements of upper-trophic-level predators, calibrated to the extent possible by existing assessments of planktonic and nektonic standing stocks and productivity for the two time periods in question. Although the parameters and estimates need further refinement, we believe that these figures represent a reasonable assessment of the key energy flows and trophic pathways through the system. At a minimum, these comparisons provide some measure of how the massive changes in the biomass of commercially important species have

⁵Field, J. C., and R. C. Francis. MS. in prep. Static and dynamic models of the northern California Current ecosystem. Fisheries Research Institute Reports.

reduced the consumption requirements upon the lower trophic levels necessary to sustain those populations.

One interesting consequence of this change is that there does not appear to be any evidence for major shifts or increases in the abundance of other species or species assemblages to take advantage of what might be perceived as an increase in the availability of forage resulting from declines in the relative abundance of commercially important predators, as has been suggested in other systems such as the Georges Bank (Fogarty and Murawski 1998). Although data on the relative abundance of target and nontarget species are sparse, preliminary work to develop diversity indices of upper-trophic-level predators based on fisheries survey data for the early 1970s and the mid-1990s also suggests no major shift in the relative composition of groundfish assemblages in the INPFC Columbia area (S. Gaichas, pers. comm.), although Emmett and Brodeur (2000) have found substantial shifts in the relative abundance of pelagic predators.

The above situation may be in contrast with other heavily fished ecosystems, in which major shifts in species or community composition have followed major disturbances. Until recently, levels of secondary production throughout the 1990s have seemed far below long-term averages; the abundance of many key forage species has been greatly reduced (Emmett and Brodeur 2000); recruitment of rockfish and survival of salmon smolts have reached all-time lows (Hare et al. 1999); and the average weight-at-age for some species, such as hake and yellowtail rockfish, have been below the long-term means (Dorn et al. 1999; Tagart et al. 2000). Massive changes in the species composition and biomass of euphausiids, copepods, and other planktonic organisms have also been documented (McGowan et al. 1998; Mackas et al., in press). All of these factors suggest that this system has probably been functioning at lower levels of productivity over recent years, as associated with the aforementioned changes in climate forcing and physical conditions following the 1977 (and perhaps 1989) regime shift (Hare and Mantua 2000). As alluded to earlier, the evidence for a large-scale climate shift that has affected the distribution and abundance of key populations in the NCC is widespread, and improving our knowledge of the mechanism and consequences of these shifts is the focus of major investigations by CalCOFI, GLOBEC, the JISAO Climate Impacts Group, and many other research entities.

The nature in which such a shift in productivity may be interacting with the concurrent and ongoing removal of a substantial fraction of the higher-trophic-level biomass in this ecosystem remains unclear. Our hope is that further insight into the nature and consequences of climate shifts, and into the interaction between such changes and ongoing effects associated with fisheries removals

might be uncovered through both static and dynamic modeling of this and other ecosystems. Over recent years dynamic models have been used to consider the impacts of fishing on marine ecosystem dynamics (Kitchell et al. 1999; Trites et al. 1999; Olson et al.⁶), and we expect that such modeling efforts might have much to offer in terms of insights toward considering large-scale ecological interactions in fisheries management.

As suggested earlier, another application of such models could be in deriving metrics or indices, which might be useful in assessing ecological health or stability, or comparing the nature and magnitude of human-induced disturbance between ecosystems. Jarre-Teichmann and Pauly (1998) used an index of the flow from primary production to higher trophic levels imbedded in the Ecopath software to assess the relative effect of fishing removals as a percentage of the production necessary to support fisheries on coastal pelagic species in several coastal upwelling systems. Their findings suggested that major fisheries for coastal pelagics removed between 1% and 15% of the primary production in these systems during distinct time periods. Perhaps more significantly, the magnitude of exploitation was more dependent upon the target species than on the total landings between systems; in other words, removals of species with higher trophic levels had a correspondingly greater effect on the percentage of primary production required (PPR) to sustain them. In these models, estimates of PPR are made for each trophic pathway, and energy flows are raised to primary production equivalents by means of methodology suggested by Ulanowicz (1995) and described in more detail in Christensen et al. (2000). The statistic of primary production required to support fisheries removals is thus a measure of the total amount of new production removed from exploited populations, scaled to the appropriate trophic level.

An example of how this index might be useful for comparative purposes is presented as figure 8. This figure shows total removals (landings and some measure of discards) in metric tons per square kilometer from three ecosystems in different time periods plotted with the estimated percentage of relative production necessary to support these landings (as above, the primary production raised to the equivalent trophic levels of the catches).

In the Eastern Bering Sea (EBS) models (Trites et al. 1999) there were massive harvests of long-lived, slow-growing predators, primarily baleen whales, sperm whales, walrus, and seals, with a corresponding low volume of landings in terms of tonnage but representing nearly all of the production at those trophic levels in that system. What this showed was essentially the "mining

⁶Olson, R. J., G. M. Watters, R. C. Francis, P. C. Fielder, J. J. Polovina, S. B. Reilly, K. Y. Aydin, and J. F. Kitchell. Climate forcing and ecosystem dynamics in the eastern tropical Pacific Ocean. MS. submitted to *Ecol. App.*

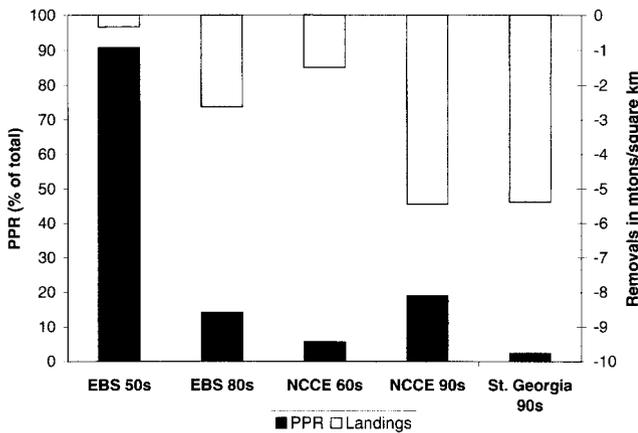


Figure 8. Fisheries removals (in metric tons/square kilometer) and percentage of primary production required (PPR) to sustain them, derived from five coastal ecosystem models. EBS = eastern Bering Sea; NCCE = northern California Current ecosystem; St. Georgia = Strait of Georgia.

out” of the biomass of higher trophic levels in the EBS during a period of intensive exploitation in the 1950s and 1960s. By contrast, in the 1980s the EBS supported the largest (by volume) fishery in the United States—the trawl fishery for walleye pollock—in addition to fisheries for Pacific cod, tanner crab, and many flatfish species. The removals (in t/km^2) increased substantially; however, due to the lower trophic levels of the target species, the percentage of system production that was removed annually declined considerably.

In the northern California Current, landings were relatively low in the 1960s, less than $1.5 t/km^2$, and the corresponding percentage of primary production required to support those landings was on the order of 6%. By the 1990s, however, the total landings had increased substantially (see fig. 4; additionally, some groundfish landings had already peaked in the 1980s and dropped by the 1990s), to an average of nearly $6 t/km^2$; this represented some 20% of the available production being removed by the fishery. By contrast, comparison with the (contemporary) Strait of Georgia model constructed by Pauly, Pitcher et al. (1998), removals were on the same magnitude between the NCCE and the Strait of Georgia in terms of tons per square kilometer, but because of the tremendous productivity and recycling of nutrients and energy in the Strait of Georgia, landings required a substantially greater percentage of the scaled production in the NCCE.

It is interesting to consider that the total removals per unit area, and the percentage of production accounted for in those removals, is greater in the NCCE than in the (contemporary) eastern Bering Sea. Whereas the latter is one of the most productive fishing grounds in U.S. waters, the immense area of this coastal shelf is what accounts for the tremendous volume of fisheries that it supports. While this construct of production required

to support landings may seem vague, and is certainly fraught with major uncertainties about the real nature of the food web that supports these landings, we believe that this example illustrates the means by which simple ecological models may show the nature and magnitude of human-induced disturbances, and ultimately may provide a useful index or tool for scaling the extent and magnitude of human intervention in these complex ecosystems.

CONCLUSIONS

McEvoy (1996) suggested that successful fisheries management will require that managers and policymakers “cooperate with each stock’s strategy for responding to the environment.” Clearly, this environment is modulated by variability and change in climate as well as increasing measures of anthropogenic disturbance. We believe that the development and application of static and dynamic ecosystem models will ultimately reveal useful insights about how both climate and fishing affect NCCE structure and dynamics, and will provide valuable insight into system definition and behavior. Additionally, we hope to illuminate gaps in research or knowledge that create potential management limitations and increase uncertainty. Finally, we believe that the development of such models will lead to both static and dynamic visualizations that readily convey to managers and stakeholders the dynamics of this ecosystem and potential or probable effects of alternative management approaches. Ultimately, such efforts should lead to the development of more refined models to quantify the nature of ecological change in this system as a result of both climate effects and fishing, and will be useful as a framework for incorporating ecological considerations into fisheries management practices.

It is fair, however, to suggest that such insights are unlikely to lead to any meaningful short-term solutions to current crises in the management of northern California Current fisheries. The salmon crisis or the massive problems associated with effectively managing the groundfish fishery and the recovery of depleted populations can be addressed only by a massive change in the way in which large-scale system variability and human-induced impacts (both fishery and nonfishery related) are mitigated and managed in the future. The adoption of an “ecosystem-based approach” will result neither in obvious solutions to current crises nor in a substitute for more traditional means of assessing and managing fisheries. As McEvoy (1996) suggests, “If scientific fishery management could not predict or maintain the production of individual species, it seems a bit presumptuous to expect that we could now anticipate and direct the interacting components of an entire ecosystem.”

Clearly, the adoption of a broader view of the inter-

actions between fisheries (both their biological and human components) and marine ecosystems is necessary, and we must accept the dynamic and inherently unpredictable nature of entire systems and learn to operate within the bounds of uncertainty to ensure future sustainability. The nature of the coastal pelagics FMP is a step in such a direction, as is the movement toward using marine reserves to provide refugia for species as well as opportunities to assess how disturbed and undisturbed systems may differ in form and function. Equally necessary are basic reforms in the current approach to fisheries management away from traditional focused command-and-control practices. These changes are not mutually exclusive; both can and must occur if the resources and the communities which depend upon them are to persist in the future.

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USING AN ECOSYSTEM MODELING APPROACH TO ASSESS THE MANAGEMENT OF A MEXICAN COASTAL LAGOON SYSTEM

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ABSTRACT

The Huizache–Caimanero coastal lagoon system supports an economically important artisanal shrimp fishery and a less valuable finfish fishery. We analyze the response of the fisheries and the ecosystem to changes in fishing effort. To do this we use Ecosim—a dynamic version of Ecopath, which is a steady-state model emphasizing natural rates of growth and consumption of marine populations. We examine changes in each group's biomass and determine which fishing strategies optimize yields on the basis of economic, social, and ecological criteria. We find that two of the four exploited fish groups, centropomids and gerreids, are underutilized; the other two, ariids and mugilids, are near the maximum sustainable yield. We find that the shrimp resource is overexploited. Our simulations suggest that the optimal management strategy occurs with a small increase in effort in the finfish fishery (1.24 times) combined with a small reduction of effort (0.8 times) in the shrimp fishery. This strategy enhances fishery yields of centropomids and gerreids, thereby decreasing the biomass of finfish and resulting in fewer (lower biomass of) shrimp predators. Simulations suggest that applying the optimal fishing strategy increases economic profits by ten percent.

INTRODUCTION

The shrimp resources of the Huizache–Caimanero lagoon system are important ecologically, economically, and socially. This lagoon complex is a nursery area for penaeid shrimp. The area has supported an important shrimp fishery since ancient times. Nearly 90% of the total shrimp catch in this lagoon is made up of one species, *Litopenaeus vannamei* Boone 1931. Three other minor species of shrimp are also caught in the fishery: *L. stylirostris* Stimpson 1874, *Farfantepenaeus californiensis* Holmes 1900, and *F. brevirostris* Kingsley 1878.

Shrimp catches in the Huizache–Caimanero lagoon system reached 1,500 metric tons in the 1980s (de la Lanza and García-Calderón 1991) and had one of the highest yields per unit area compared with other coastal lagoons (Edwards 1978), but catches have declined in the last decade. A finfish fishery in the area exploits four groups: centropomids, ariids, gerreids, and mugilids. On

the basis of economic value and catch volume, however, the finfish fishery is less important than the shrimp fishery.

An Ecopath mass balance model (Christensen and Pauly 1992) has been developed by Zetina-Rejón (2000) using available information for the Huizache–Caimanero lagoon system. This model describes the trophic structure and energy flow among the major functional groups in the ecosystem. In this paper, we use the model to evaluate the status of the current fisheries and to explore optimization of fishing strategies based on ecological, economic, and social criteria.

MATERIALS AND METHODS

Study Area

The Huizache–Caimanero lagoon complex is located on the Pacific coast of Mexico in the south of Sinaloa state (fig. 1). A narrow channel separates the two lagoons, and a barrier island separates the lagoons from the Pacific Ocean. Each lagoon receives intermittent flows from two small rivers connected by narrow, winding channels, permitting the transport of fresh water out of the lagoon during the rainy season (June to January). A contorted channel, permanently open, allows shrimp postlarvae and other marine species to enter the lagoons shortly after spawning. Tides are semidiurnal, with a range of 0.85 m. The average area of the system is 175 km², and is reduced dramatically to 65 km² in the dry season (Soto 1969). Water temperature ranges from 20° to 40°C, and precipitation varies between 800 and 1,200 mm per year (de la Lanza and García-Calderón 1991). Mangrove swamps and other halophytes surround the lagoon complex.

The Shrimp Fishery

Shrimp are caught by means of artificial barriers, locally known as *tapos*, which are placed in tide channels. This method catches subadult shrimp during their emigration to the sea. Each tapo has two or more heart-shaped collectors pointing downstream so that shrimp are caught inside at ebb tide. There are platforms around the collectors on which fishermen stand and remove shrimps with scoop nets. During fishing operations there

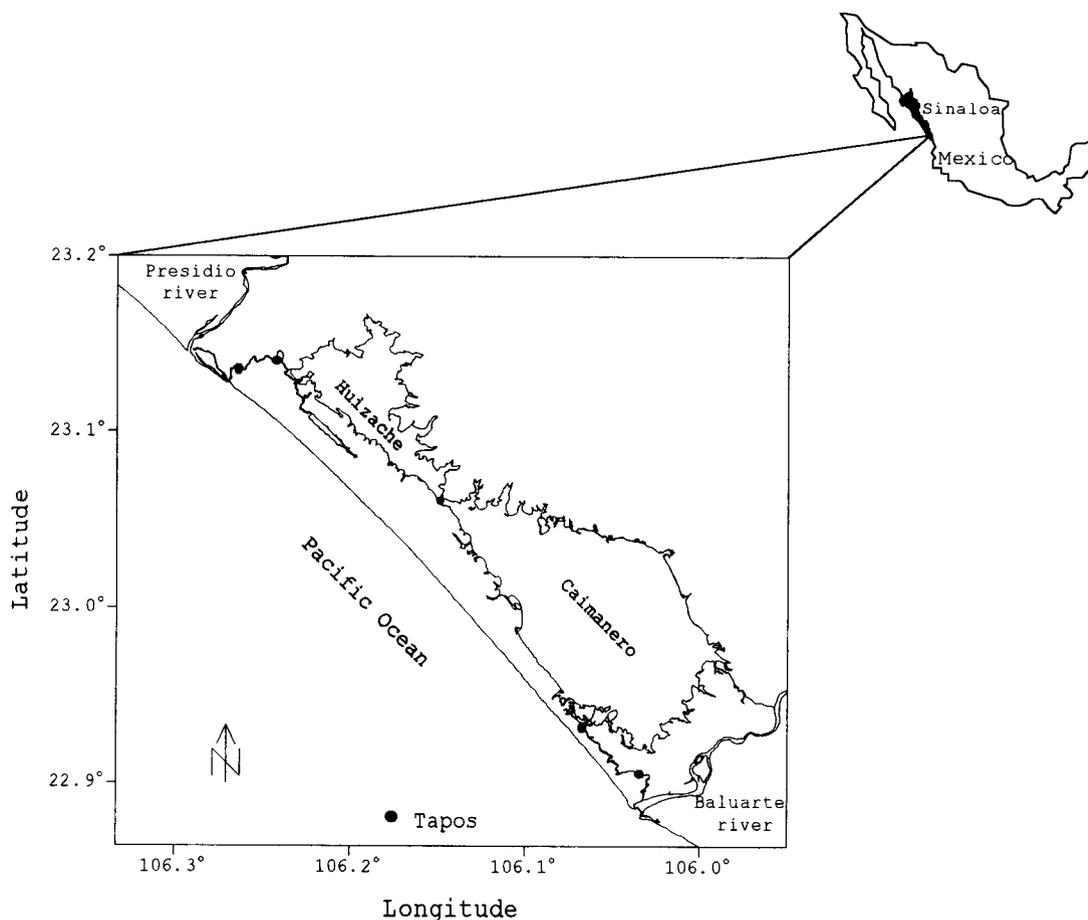


Figure 1. Huizache-Caimanero coastal lagoon system, with *tapos* indicated.

is no bycatch. The fishery lasts from mid-September to mid-April, when the *tapos* are closed.

Model Construction

Zetina-Rejón (2000) constructed a mass balance model for the Huizache-Caimanero coastal lagoon system by using Ecopath with Ecosim software (Christensen et al. 2000). The model includes 26 functional groups based on the economic or ecological importance of species. Two groups of primary producers (phytoplankton and macrophytes) and a detritus group were also included in the model (fig. 2). The Ecopath model (Polovina and Ow 1983; Polovina 1984; Christensen and Pauly 1992) uses a set of linear equations for all groups i in the system and assumes mass balance; that is, the production of the i group minus all predation on i minus nonpredatory losses of i minus export of i is equal to zero. This is formulated as:

$$B_i \cdot \left(\frac{P}{B}\right)_i \cdot EE_i - \sum_{j=1}^n B_j \cdot \left(\frac{Q}{B}\right)_j \cdot DC_{ji} -$$

$$B_i \cdot \left(\frac{P}{B}\right)_i \cdot (1 - EE_i) - EX_i = 0 \quad (1)$$

Where B_i = biomass of group i ;

$(P/B)_i$ = production/biomass ratio of i , which is equal to the total mortality coefficient (Z) under steady-state conditions (Allen 1971; Merz and Myers 1998);

EE_i = ecotrophic efficiency, which is the part of the total production that is consumed by predators or exported out of the system;

B_j = biomass of predator j ;

$(Q/B)_j$ = consumption/biomass ratio of predator j ;

DC_{ji} = proportion of prey i in the diet of predator j ;

EX_i = the export of group i , which in this study consists of catch if the group is exploited.

Since this equation is balanced, a term can be unknown and the model will estimate it. In addition, the diet composition of all consumers is required.

Simulation of Harvesting Strategies

We use Ecosim (Walters et al. 1997), the time dynamic version of Ecopath, to simulate changes in fishing rate for the exploited groups. Ecosim takes the set of linear equations used in Ecopath and re-expresses them as coupled differential equations where the term biomass accumulation may equal zero. Ecosim's basic equation is

$$\frac{dB_i}{dt} = f(B) - M_o B_i - F_i B_i - \sum_{j=1}^n c_{ij}(B_i, B_j) + BA_{cc} \quad (2)$$

where B is biomass;

M_o is the mortality rate (not due to fishing or predation);

F_i is the fishing mortality rate;

$f(B)$ represents the production function if the group is a primary producer or the growing function if the group is a consumer;

$C_{ij}(B_i, B_j)$ is the function to predict the consumption of the prey i by predator j ;

BA_{cc} is the biomass accumulation term.

Ecosim uses some parameters additional to those used in Ecopath. These include vulnerability settings for all predator-prey interactions, which control the rate at which prey move between a vulnerable state and an invulnerable state. This vulnerability setting allows us to impose trophic flow, using either "top-down" or "bottom-up" control. The first control often leads to rapid oscillations of prey and predator biomasses, and the second often leads to unrealistically smooth biomass changes in prey and predator dynamics, which usually do not propagate through the food web. In this study, we used $v = 0.3$, which represents a mixed control, since we have no information on whether the system is controlled from the top down or from the bottom up.

An additional input is the maximum production/biomass ratio tolerated by any group. This value is used to limit the value of P/B when fishing or predation increases for a group. A maximum P/B value twice that of the original was used in this study.

Equation 2 permits us to simulate perturbations in fishing intensity (F_i) for any group to describe biomass changes, taking into account growth rate, consumption, and mortality not due to fishing. We use the equilibrium analysis to evaluate the changes resulting from different levels of fishing effort. This analysis takes the partial derivatives of the differential equations defined by Ecosim with reference to fishing mortality, and sets these equal to zero. Ecosim then finds the catch tendency and biomass values of all groups that would result from differ-

ent fishing levels expressed as fishing mortality. The analysis was performed for each fleet separately—the shrimp fleet, which we modeled as a single-species fishery *L. vannamei* (since this is the most important and abundant species); and the finfish fleet, which catches four fish groups: centropomids, ariids, gerreids, and mugilids. For each exploited group, we explored the fishing mortality from $F = 0$ up to $F = 3\times$ (three times the original value).

In order to find F values that optimize management strategies, we used the fishing strategies optimization searching procedure included in Ecopath with Ecosim software version 4.0 (Christensen et al. 2000). This procedure takes into account the maximization of an objective function based on ecological, economic, and social criteria. The ecological criterion (E) is defined by the importance of each group in the ecosystem based on the inverse of the P/B ratio for each group, which is related to the longevity of the organism (Christensen 1995). The economic criterion ($\$$) is defined as the total landed value of the catch minus the total operating cost. The social criterion (J) is assumed to be proportional to the index jobs/catch landed value for each fleet. Weighted values are assigned to each criterion depending on the management strategy to be evaluated. In this case, we tested several relative weights for each criterion, and found the best results with values of 1.9 for social and economic criteria and a value of 1 for the ecological criteria. The ecological criteria often imply reduced fishing effort for large, long-lived organisms, in this case represented by top predators, some of which are exploited in the finfish fishery.

The optimization routine uses the Davidson-Fletcher-Powell nonlinear estimation method, which iteratively maximizes the 3-criteria objective functions affecting the fleet structure and deployment through changes in fleet size. The relative fleet sizes are used to calculate relative fishing mortality rates for each fleet type. We assume that reducing a fleet type by some percentage results in the same percentage decrease in the fishing rates for all the groups that it catches. In this study, simulations were performed for period of 30 years. The optimization was started at year 5 to year 30, and the fleets were independently optimized at the same time.

The former simulation corresponds to an approach aimed at reaching a broadly defined goal, a policy assessment known as "open-loop." Additionally, Ecosim incorporates a "closed-loop" policy simulation to evaluate not only the biomass dynamics over time, but also the dynamics of the stock assessment and regulatory process. That is, a closed-loop simulation considers the uncertainty in biomass and fishing rate estimates. Assessment results are implemented through limitation of fishing effort. The closed-loop simulation permits one

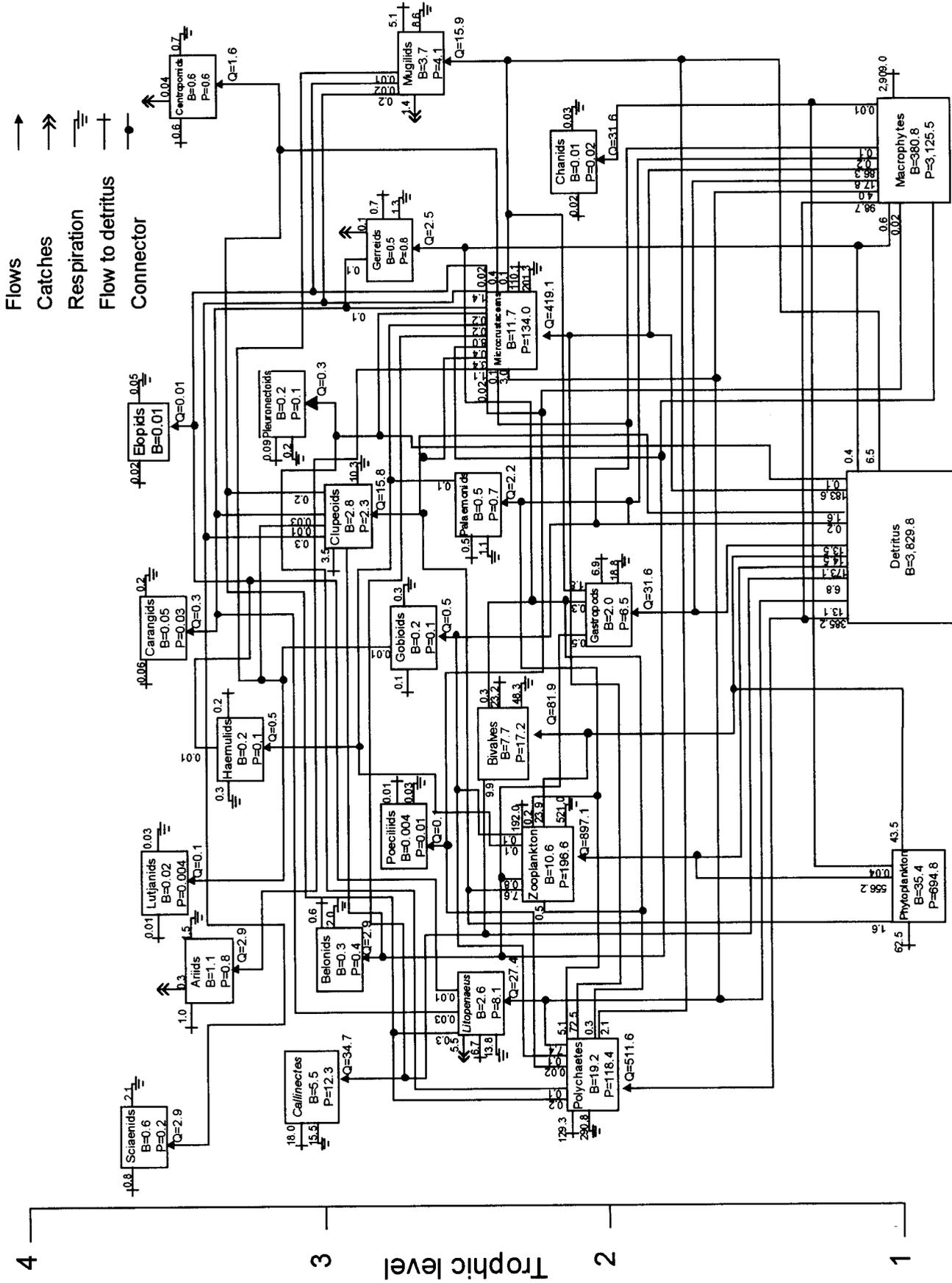


Figure 2. Box model representing major flows in Huizache-Caimanero coastal lagoon system, using Ecopath approach. B = biomass ($g \cdot m^{-2}$), P = production ($g \cdot m^{-2} \cdot year^{-1}$), Q = consumption ($g \cdot m^{-2} \cdot year^{-1}$). After Zeina-Rejón 2000.

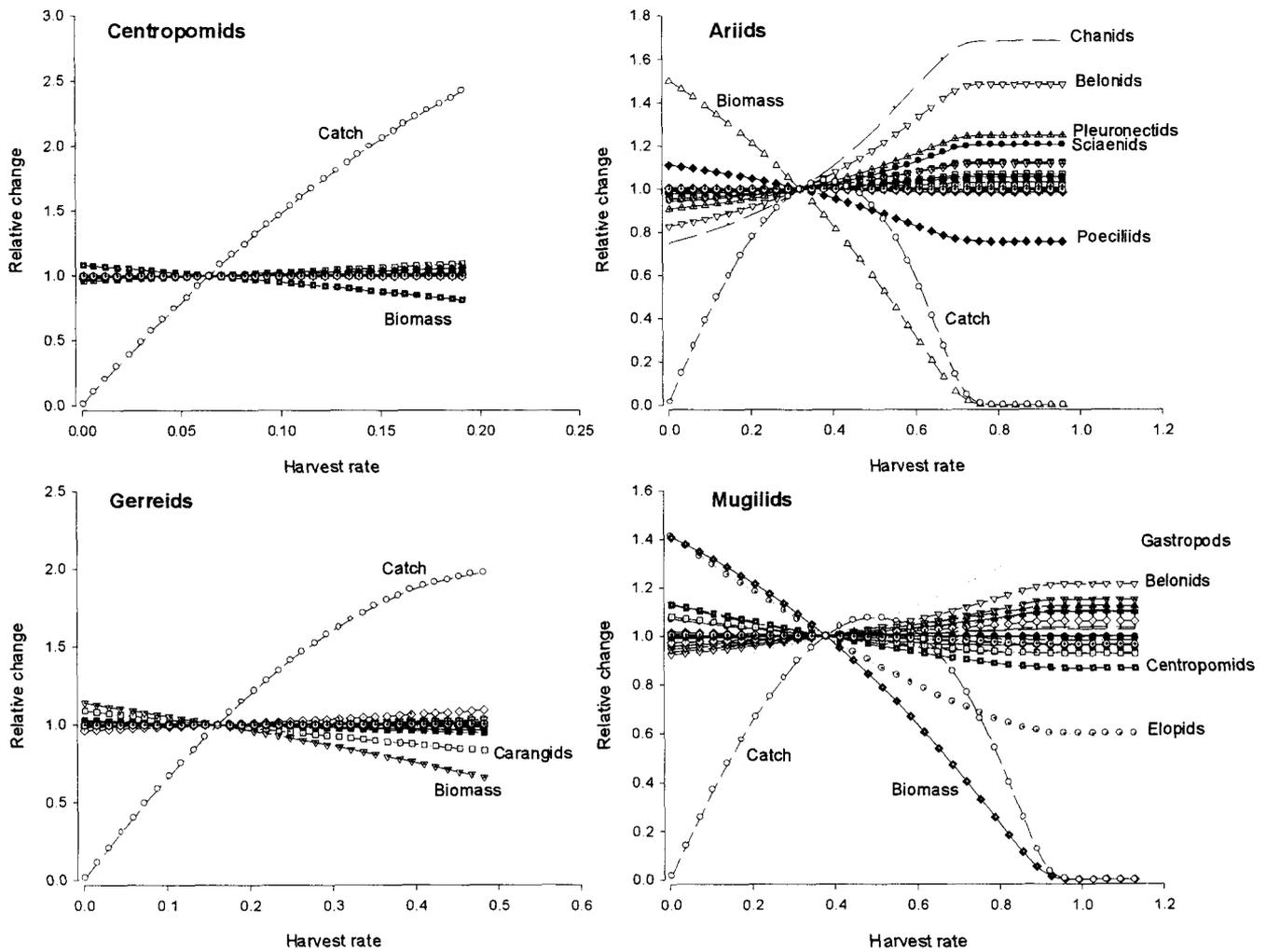


Figure 3. Simulation of changes in biomass and catches of exploited groups resulting from changes in fishing effort of finfish fleet. For each group the simulated harvest rate ranges from 0 up to 3 times the original value, which corresponds to the intersection point of all curves. The only other groups indicated are those with major changes in biomass.

to (1) decide how many closed-loop stochastic simulation trials to do (in this case 10); (2) set the accuracy of the annual assessment procedures coefficient of variation of annual biomass estimates (in this case 20%); (3) set the value or importance weightings for the F 's imposed on various species by each fishing fleet (in this case the same impact was considered for all exploited groups); and (4) consider changes in catchability as the maximum annual increase (in this case a value of 0.1 was used). In this study, we use the closed-loop simulation results for analyzing the risk of exceeding upper and lower biomass bounds for any group—0.5 and 2.0 times the original biomass, respectively—as a consequence of implementing the optimized management strategy.

RESULTS

Although current catches of ariids and mugilids are near the maximum sustainable yield, changes in fishing

effort do not appear to affect the biomass of centropomids and gerreids because current levels of exploitation are low, as indicated by equilibrium analysis (fig. 3). In contrast, simulations show that the shrimp fishery is over-exploited (here defined as exploitation beyond the maximum biological production), as indicated by the current fishing effort on the right side of the curve that represents the maximum yield (fig.4). We find that changes in fishing effort not only directly affect the exploited groups but also indirectly affect other groups that interact with exploited species.

Changes in effort in the finfish fleet that intensively exploit ariids and mugilids seem to affect more groups than just the centropomids and gerreids, which are less exploited in the system. The groups affected by this fleet are from different trophic levels, including such top predators as elopids, carangids, and centropomids, as well as organisms from the second trophic level such as chanids,

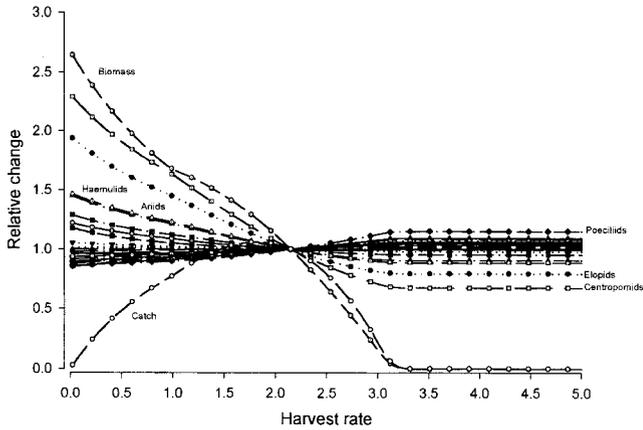


Figure 4. Simulation of changes in biomass and catches of exploited groups resulting from changes in fishing effort of shrimp fleet. For each group the simulated harvest rate ranges from 0 to 3 times the original value, which corresponds to the intersection point of all curves. The only other groups indicated are those with major changes in biomass.

poeciliids, and gastropods (fig. 3). The shrimp fleet, which is intense, impacts several groups in higher trophic levels, mainly top predators such as elopids, centropomids, ariids, and haemulids (fig. 4).

After the optimization routine was run during simulation, the resulting fishing effort for the finfish fleet suggests an increment of 1.24 times the original fish mortality, and for the shrimp fleet a reduction at 0.80 times the original value. We did not find any important reduction in the biomass of any group, but a small increase in shrimp biomass resulted from the reduced fishing effort even when uncertainty was considered (closed-loop). Also, the biomass of ariids and mugilids was slightly reduced as a consequence of the fishing effort in the finfish fishery (fig. 5).

Furthermore, in all cases we found changes in catches (figs. 6 and 7) after year 5 following the change in fish-

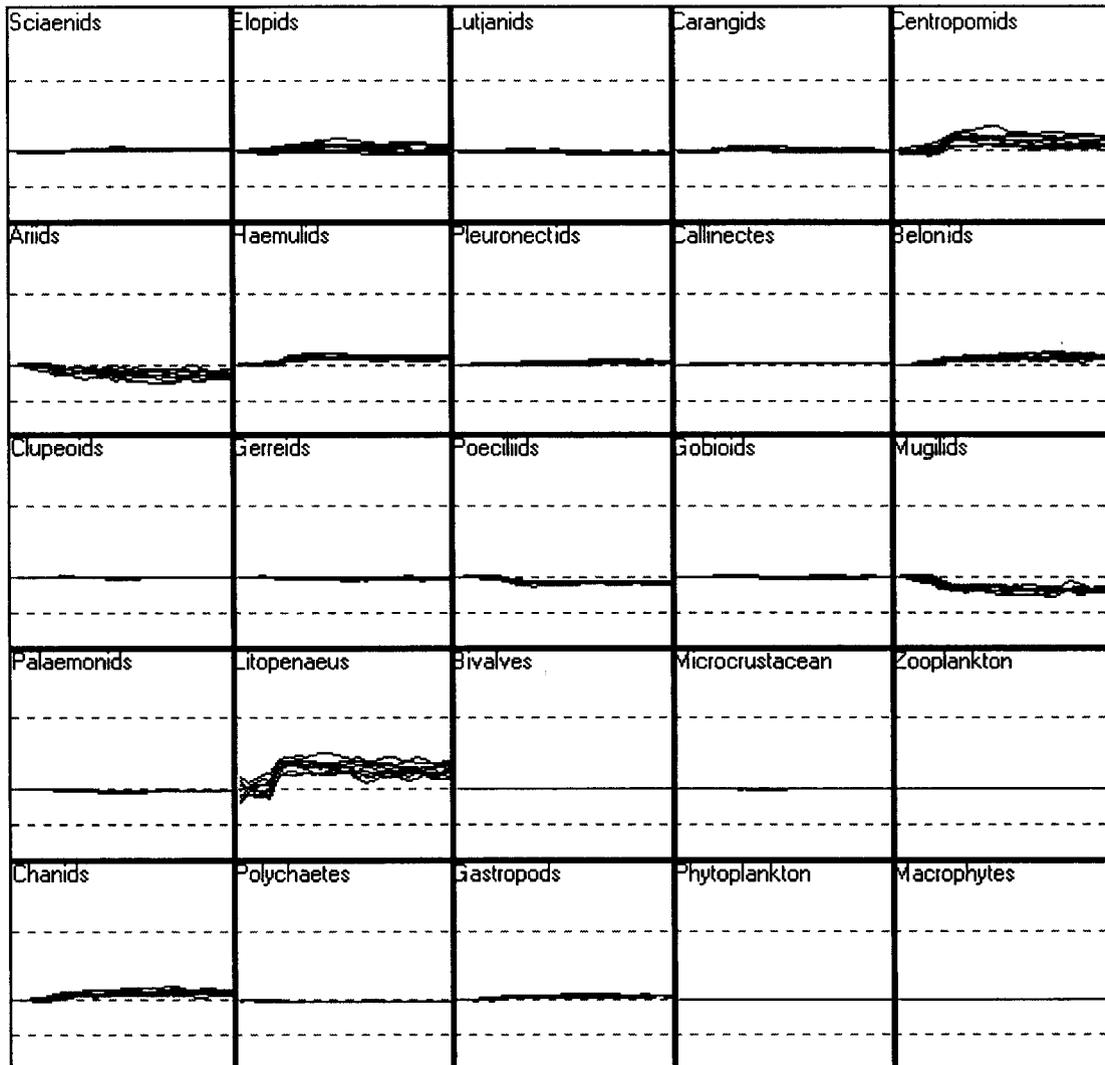


Figure 5. Biomass trends of groups after optimization of management strategies considering economical, social, and ecological criteria and considering closed-loop policy simulation. Black lines represent uncertain biomass. Upper and lower dotted lines represent levels of biomass as 2.0B and 0.5B, respectively.

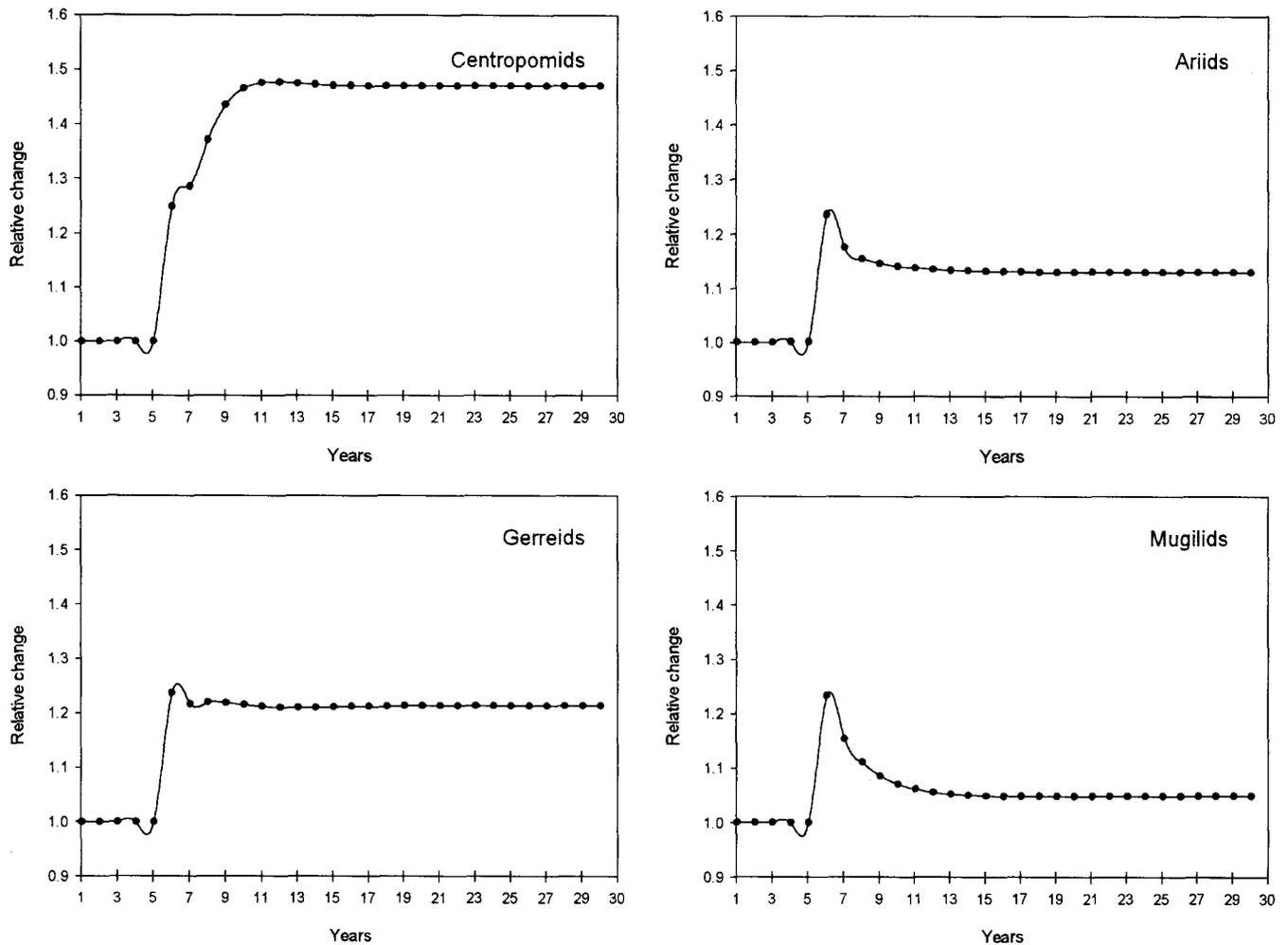


Figure 6. Relative catches of each group caught by finfish fleet, after optimization of management strategies considering economical, social, and ecological criteria.

ing effort, showing variability in yield which tended to reach stability over time. The major changes in yield were for centropomids, with increases of 1.5 times the original catch. The shrimp yields also present increments near 10%, important because shrimp is the most valuable resource in the area.

Outputs for the three criteria considered in this study, after the optimization procedure, were compared with initial values without optimization (current state). The results are shown in table 1 as relative values (optimized criteria value divided by initial value) for both policy assessments. The results of both procedures, open- and closed-loop, are consistent and suggest that the optimal management strategy can increase economic benefits by 10 percent. The other two criteria, social and ecological, were not reduced in either analysis (deterministic or stochastic).

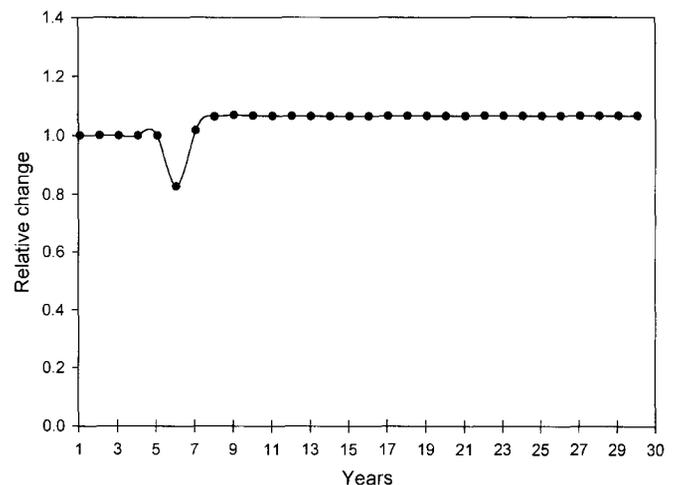


Figure 7. Relative catches by shrimp fleet, after optimization of management strategies considering economical, social, and ecological criteria.

TABLE 1
**Relative Values of Each Criterion after Optimization
 of Fishing Management Strategies**

	Criteria		
	\$ Economic	J Social	E Ecological
Open-loop assessment	1.13	1.06	1.02
Closed-loop assessment	1.09	1.05	1.02

DISCUSSION

Multispecies management has been a challenge because management efforts have traditionally focused on single species (Walter and Hoagman 1971; Pope 1979; Kirkwood 1982; Sainsbury 1982; Cushing 1984; Gulland and García 1984; Christensen 1998). Ecosystem-based approaches incorporating trophic structure offer a tool for understanding how ecosystems function and for evaluating which fishing strategies are optimal for areas with multiple interacting fisheries (Walter 1979; Polovina and Ow 1983; Polovina 1984; Christensen and Pauly 1992; Walters et al. 1997). Furthermore, simulation models have shown the relevance of the multispecies approach, since fishing has been shown to affect resources both directly and indirectly (Arreguín-Sánchez and Chávez 1995; Arreguín-Sánchez and Valero 1996; Christensen 1996; Arreguín-Sánchez and Manickhand-Heileman 1998), as well as ecosystem structure (Pérez-España and Arreguín-Sánchez 1999). The results of these model simulations can be used to make recommendations to optimize fishery management.

Recently, researchers have been discussing how ecosystem-based approaches can be used to guide fishery management (Pauly 1998; Field et al., this volume; Fluharty and Cyr, this volume). Discussions have focused on the application of tools to evaluate multispecies fisheries in order to develop a comprehensive framework for management (Arreguín-Sánchez, in press; Arreguín-Sánchez and Calderón-Aguilera, in press). This paper focuses on how to optimize fishing in a coastal lagoon system in which there are valuable shrimp resources and less valuable finfish resources.

We find that the two more valuable finfish resources (centropomids and gerreids) are underexploited, and that higher profits could result from increased fishing effort on them. This increased exploitation would reduce the biomass of finfish in the system, and there would be a concomitant reduction in the biomass of shrimp predators. A large increase in fishing effort for finfish, however, could deplete the other two fish groups: the ariids and mugilids. Furthermore, not only would the centropomids and gerreids be directly affected by large increases in fishing effort, but our results show that other groups would sustain an indirect negative effect (fig. 3).

Our model predicts that the most heavily affected groups would be from the top and middle trophic levels.

The results of both equilibrium and optimization analyses were in agreement, suggesting that a small decrease in shrimp fishing effort and a small increase in finfish effort would be optimal. In fact, fishing efforts resulting from the optimization procedure are near the F_{MSY} indicated by equilibrium analysis (figs. 3 and 4). The use of ecological criteria in the optimization procedure reduces the possibility of biomass depletions; therefore the optimum fishing strategy did not greatly increase fishing effort for finfish. Our model predicts an increase (10%) in economic profit with the application of the optimal fishing strategy. This increase occurs in our simulations even after we account for uncertainty in the data estimates as well as the assessment procedures (closed-loop).

In our examinations of the vulnerability parameter, we observed lower changes in biomass estimations for bottom-up control ($\nu < 0.3$); whereas top-down control ($\nu > 0.3$) produced abrupt changes in biomass estimations. The lowest uncertainty was observed for the mixed control model ($\nu = 0.3$). Similar results have been reported by Arreguín-Sánchez (in press), who also suggests that assuming bottom-up control often leads to higher uncertainty in biomass estimates for groups from intermediate trophic levels, and top-down control can lead to higher uncertainty for biomass estimates for groups from higher trophic levels. Clearly, this is an area for further investigation, since the mechanisms behind the observed behavior could help explain what occurs in ecosystems where top predators have been removed by fishing. However, using a mixed control in the model produces less uncertainty in biomass estimates than bottom-up or top-down controls, and could help us to detect average biomass responses resulting from the implementation of optimum fishing strategies.

Our results show a practical application of trophic modeling to a coastal lagoon system. Furthermore, this method allows us to model the effects of various levels of fishing effort on target resources. This example highlights how assessments like these can predict the ways in which multispecies fisheries can affect each other. Multispecies modeling can be used to predict changes in biomass of all the groups in the ecosystem as a result of changes in fishing effort. Furthermore, this example shows how such modeling can be used to optimize fishing strategies, thereby enhancing economic profits from multispecies fisheries.

ACKNOWLEDGMENTS

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DISPERSING OIL NEAR SHORE IN THE CALIFORNIA CURRENT REGION

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ABSTRACT

Mathematical models were used to develop scenarios for evaluating alternative nearshore responses to oil spills, including the use of chemical dispersants. The scenarios were used in ecological risk assessment (ERA) workshops designed to help fisheries, wildlife, and resource managers determine whether they would support preapproving the use of dispersants. Resource managers proposed a worst-case spill scenario for the Gulf of the Farallones. Models were used to compare five options—no response, mechanical, burning, and two levels of dispersants—showing the trajectories, fate, and concentration of oil in surface slicks and dispersed oil plumes. Participating biologists used current data on dispersant and dispersed oil toxicity to develop consensus-based toxicity guidelines. During the first several hours following dispersal, the simulated dispersed oil concentrations exceeded guidelines for early life-history stages of fishes and zooplankton; adult fish and crustaceans were at risk for two hours. The benefits and risks to fishes, seabirds, cetaceans, pinnipeds, sea otters, and shoreline resources (marshes, kelp beds, and protected areas) were compared for the five response options. Dispersants substantially reduced the amount of both floating and stranded oil relative to the other options. Furthermore, the higher dispersant level (85%) removed more oil than the lower level (35%). Risk assessments so far indicate that chemical dispersion can reduce the overall ecological effects of a nearshore oil spill. The final decision to preapprove dispersant use along the Pacific Coast will still require input from the political, social, and economic sectors.

INTRODUCTION

Chemical dispersion is an often-debated method for responding to oil spills, yet it is rarely used. During the past 30 years, mechanical containment and recovery, extensive shoreline cleanup, and highly publicized bird and wildlife rehabilitation have been the primary responses to oil spills along the coasts of Washington, Oregon, California, and northern Baja California. There is renewed interest in using dispersion as a response to reduce injuries to wildlife and shoreline oiling in the California Current region.

Dispersants are most effective when used early in a spill. Chemical dispersants are currently permitted on a case-by-case basis in Oregon, Washington, and offshore areas of California. Since most spills begin near shore, there is interest in preapproval or quick approval for dispersing spills in shallow water. Approval requires consultation with resource agencies at the time of a spill. Preapproval can greatly reduce decision time and help ensure that dispersion capability is available.

Recently, ecological risk assessment (ERA) workshops were held in Washington, Texas, and California to inform resource managers about traditional and alternative responses to oil spills as well as the need for preapproval, quick approval, or shallow-water approval processes (Aurand et al. 2001; Kraly et al. 2001; Walker et al. 2001). These workshops, supported by the Hazardous Materials Response Division (HazMat) of the National Oceanic and Atmospheric Administration (NOAA), focused on oil spill simulations to evaluate the efficacy of response.

This paper summarizes our current knowledge of dispersants, dispersing oil, the need for preapproval, methods used to simulate spill responses, and ecological risk assessment. In addition, we compare scenarios for dispersed and nondispersed oil spills, examining the trajectory, fate, and effects of a simulated oil spill near shore in northern California at the Gulf of the Farallones.

BACKGROUND

Dispersants and Dispersion

Dispersants are chemicals that break up oil slicks. Dispersants, such as Corexit 9500 and Corexit 9527, contain surfactants and solvents which reduce the surface tension of floating oil (NRC 1989; S. L. Ross 1997). During dispersant operations, neat or diluted mixtures of dispersants are loaded onto aircraft or boats and sprayed as a fine mist directly on the oil slicks. The dispersant mixture causes the oil to break up into tiny (10 to 100 micron) droplets. With adequate wave energy, such as a light wind chop, the oil droplets mix down into the water column and spread laterally, resulting in turbid clouds or plumes of oil within a few meters of the sea surface. Over the next few minutes and hours

these plumes continue to dilute by mixing laterally and downward, and move out of the spill area with prevailing currents.

Treating oil slicks with dispersants quickly breaks up and submerges oil, effectively reducing the risk of oiling sea birds, marine mammals, and sensitive shorelines (NRC 1989). Dispersion also appears to greatly increase the rate at which oil is degraded (Cretney et al. 1981; Swannel and Daniel 1999) and, if used early in a spill, may help prevent the formation of water-in-oil emulsions (chocolate mousse) and tar balls (NRC 1989).

Dispersion effectiveness is limited by several constraints: (1) the oil must be dispersible (some heavy oils are not); (2) there must be sufficient wave energy to mix dispersed oil into the water column (light chop a minimum); (3) treatment must be done during the first few hours after the spill (weathered oil is less dispersible than fresh); and (4) the operation must be logistically feasible (NRC 1989). Conventional wisdom has held that the window of opportunity—the set of physical and temporal conditions that allow chemical dispersion to be effective—is narrow and generally limited to the first few hours to a day after a spill and to a modest range of fuel and oil types (NRC 1989; Reed et al. 1999). Thus the decision to disperse must be made quickly if it is to be effective.

Ironically, all response options, including dispersants, skimming, and shoreline cleanup, can also redistribute oil and cause ecological injuries above and beyond those caused by an untreated spill (table 1; API, in press). Finally, oil may disperse without application of chemical dispersants, because many light and medium oils disperse naturally (NRC 1989). Such was the case with the highly lethal *Tampico Maru* diesel spill in a cove off Baja California in 1958 (North et al. 1964).

Obviously, the benefits of intentionally dispersing oil must be weighed against possible damage to life in the water column, including fish and fish habitat. Both dispersants and fresh oil are toxic to zooplankton and sensitive life stages of fishes and invertebrates; oil is the more toxic of the two (NRC 1989; Singer et al. 1998; Clark et al., in press). Although dispersed oil does not sink to the seafloor, plumes of dispersing oil mix and mingle with the plankton and may drift over shallow-water benthic habitats such as oyster and clam beds or populations of shrimp, demersal fish, or sea grasses (if dispersed near shore). These organisms may become temporarily contaminated with oil or petroleum hydrocarbons (Page et al. 1983; NRC 1989; Michel and Henry 1997). If dispersed oil concentrations are high enough, and exposure long enough, populations may be injured or killed.

Historical research on dispersants included field trials in southern California in the 1970s using intentionally spilled and dispersed oil (McAuliffe et al. 1981).

TABLE 1
Countermeasures Available to Marine Spill Responders and Some of Their Ecological Impacts

Countermeasure (stressor)	Ecological impact
No response (natural recovery)	Low if oiling light
Open water response	
Containment boom	Oil in undertow water; chain rips sea grass
Skimmers	Noise; air pollution
In situ burning*	Smoke
Chemical dispersion*	Water column toxicity
Chemical herding*	Toxicity?
Shoreline cleanup	Injure eggs of shore spawners
No action (natural recovery)	Slow; toxicity; smothering
Manual removal	Damaging foot traffic
Mechanical removal	Physical shoreline damage
Sorbents/passive collection	Excess waste generation
Vacuum	Fuel consumption; foot traffic
Sediment reworking/tilling	Sediment physical damage
Berm relocation	Resuspension/dispersion
Surf washing	Resuspension/dispersion
Vegetation cutting/removal	Stress to marsh if not careful
Burning*	
Marsh	Smoke; combustion of biota
On beaches	Smoke
Deluge flooding	Nearshore oil dispersion
Ambient-temperature washing	
Low pressure	Nearshore oil dispersion
High pressure	Mortality to surviving biota
Warm and hot water washing	Mortality to surviving biota
Sand and slurry blasting	Mortality to surviving biota
Chemical countermeasures*	
Shoreline cleaners	Toxicity; dispersion
Solidifiers	Not enough experience
Bioremediation*	
Nutrient enhancement	Nutrient, metabolite toxicity
Bacterial inocula	Metabolite toxicity; nonindigenous microbes

Note: Each response is effective under certain conditions, but each can cause collateral effects or redistribute oil.

*Requires special approval.

Assembled from various sources, including API, in press, and Mearns 1996.

These sea trials provided not only a reality check for operations and monitoring but also necessary data for developing and testing mathematical models for forecasting dispersed oil concentrations in water (MacKay et al. 1982). Dispersion operations were approved at two California spills in the 1980s: the tanker *Puerto Rican* spill in November 1984 (Zawadski et al. 1987) and the *Pac Baroness* spill near Point Conception in September 1987 (Payne et al. 1991). These operations were limited, and their effectiveness was equivocal.

New Information in the 1990s

In a detailed review of dispersant use, fate, and effects, the National Research Council identified a number of uncertainties (NRC 1989). These uncertainties have been mostly resolved during the 1990s. The principal concerns were fate and toxicity (Aurand 1995a) and poor communication of existing knowledge (Bostrom

TABLE 2
 Oiled and Dead Birds Recovered during Six California Oil Spills

Year	Incident	Location	Oil type	Volume L (gallons)	Number of oiled birds recovered
1990	<i>American Trader</i>	Huntington Beach	ANS Crude	1,514,000 (400,000)	1,017
1993	UNOCAL	Avila Beach	San Joaquin	23,846 (6,300)	>100
1997	<i>Kiue</i>	Humboldt Bay	IFO 180	946,250 (250,000)	984
1997	Mystery spill	Point Reyes	Crude	No data	>500
1998	Mystery spill	Santa Cruz	Unknown	No data	1,535
1999	<i>Stuyvesant</i>	Eureka	IFO 180	7,570 (2,000)	1,270

Source: Michael Sowby, California Oil Spill Prevention and Response, Sacramento, October 2000, personal communication.

et al. 1997). During the 1990s several coordinated industry, government, and academic field and laboratory activities resolved issues dealing with dispersed oil fate and toxicity (Aurand 1995b; S. L. Ross 1997; Singer et al. 1998; Rhoton et al. 1999; George-Ares and Clark, 2000; Page et al. 2000; Clark et al., in press). The toxicity studies included sensitive early life stages of California Current nearshore organisms such as kelp mysids, giant kelp sporophytes, and larval abalone (Singer et al. 1998). Dispersant formulations have been refined, and there is a considerable body of new knowledge about their effectiveness (Clayton et al. 1993; Lunel et al. 1997; S. L. Ross 1997; Fiocco et al. 1999b; Lunel and Lewis 1999; Lessard and DeMarco 2000). The results of direct field trials (intentional oil spills) indicate that the conventional window of opportunity has widened to increase response time to two days, accommodate heavier oils, and lower dispersant-to-oil ratios (S. L. Ross 1997; Fiocco et al. 1999a). Finally, there are new data from laboratory, mesocosm, and field studies about oil-dispersion processes, better numerical models, and more effective treatment operations. These studies all suggest that more spills may be suitable for the use of dispersants.

Equally important is new and controversial information suggesting that small amounts of oil remaining after even extensive shoreline cleanup are sufficient to injure embryos of shore-spawning fishes such as Pacific herring (*Clupea pallasii*) and pink salmon (*Oncorhynchus gorbuscha*; Kocan et al. 1996; Marty et al. 1997; Carls et al. 1999; Heintz et al. 1999). Indeed, aggressive shoreline cleanup itself disperses oil into very shallow water, damages surviving shoreline biota, and delays recovery of shoreline habitat (table 1 and Mearns 1996). Thus, efforts to prevent shoreline oiling (through dispersant use) can reduce the long-term effects of an oil spill on fish habitats such as sediments, marshes, eelgrass, and kelp beds. Although this new knowledge raises more questions, it also brings into clearer focus important trade-offs of all response options.

Assessment of Oil Spill Risk

There has been a worldwide decline in both the volume of oil spilled and the frequency of very large oil

spills (3.8 million liters or 1 million gallons) during the past decade (Etkin 1999). In the California Current region, however, there is no long-term trend for the 22-year period 1978 through 1999 for midsize spills greater than 37,850 L (10,000 gal).

Previous spills in the California Current region included 155 coastal and marine incidents involving a total spillage of 70 million L (18.5 million gal) of oil and fuel products. This total is about twice that spilled by the *Exxon Valdez* in Alaska. Of the California Current region spills, 121 occurred in California (61 million L, or 16 million gal), 25 in Washington (7.4 million L, or 1.95 million gal), and 9 in Oregon (1.8 million L, or 0.47 million gal). Per mile of shoreline, these 22-year totals are: California, 4,670 gal, or 17,800 L per mile; Oregon, 330 gal, or 1,280 L per mile; and Washington, 640 gal, or 2,450 L per mile. Many of these involved highly dispersible products.

Smaller spills (0.04–0.38 million L, or 10,000–100,000 gal) continue to occur with fishing and cargo vessels, pipelines, and shore facilities, so fish and wildlife continue to be injured regardless of spill volume. During the past decade thousands of sea- and shorebirds have been oiled from nearshore spills in the California Current region. We estimate that since 1990 more than 5,000 birds representing over 25 species were recovered oiled or oiled and dead in six notable California spills (table 2). These counts represent only a small fraction of the actual number injured, which were not counted.

Historically, there have been many lost opportunities in the United States to use dispersants to protect shorelines and wildlife. Kucklik and Aurand (1997) reported that of 207 spills of oil and fuel larger than 159,000 L (1,000 bbls, or 42,000 gal) between 1973 and 1994, 60 could have been treated with dispersants on the basis of oil type (dispersibility) and weather conditions. Most of these spills occurred near shore, well within individual state-defined limits of 2 or 3 nautical miles (nmi; or 3.7 and 5.6 km) or the 33 ft (10 m) or 60 ft (approximately 20 m) isobaths, inside of which there is currently no preapproval in the United States (other than Hawaii). Presumably many more smaller spills that were potential candidates for dispersion went unreported.

Current Dispersant-Use Policy

During the 1990s dispersants were preapproved for use in most U.S. Atlantic and Gulf of Mexico coastal waters beyond 2 or 3 nmi (3.7 or 5.6 km) and beyond the 33 or 60 ft (10 or 20 m) isobaths. For oil spills beyond this nearshore zone, in these regions, the U.S. Coast Guard (USCG) federal on-scene coordinator (FOSC) is preauthorized to order dispersant applications without additional consultation with state and federal resource trustees. During the last four years, under preapproval guidelines, at least four oil spills have been treated with dispersants in Louisiana and Texas (Calhoun et al. 1997; Gugg et al. 1999). In addition, the USCG and NOAA HazMat supported dispersant use at recent (2001) spills in the Galápagos Islands and near Barbers Point in Hawaii.

Dispersant preapproval has not been implemented for the U.S. West Coast. Dispersants are not banned in Washington or Oregon, but they cannot be used in in-shore waters without deliberation and consultation on a case-by-case basis (at the time of the spill). In Washington a preapproval plan exists (WDOE 1993), but has not been implemented pending state approval of a monitoring plan. In Oregon, dispersant use remains on a case-by-case basis; Oregon has accepted the Washington guidelines, but has not yet applied them to a preapproval process. In California, preapproval does not exist, but the state does support an explicit "expedited" decision process: case-by-case use will be considered for spills beyond 0.5 nmi or the 60 ft (approximately 20 m) isobath, whichever is more restrictive. In all three states there is growing interest to preapprove dispersant use and to develop and stage dispersant response capabilities (chemicals, delivery systems, and aircraft).

The Preapproval Process in the California Current Region

The new knowledge gained since the 1989 NRC review sets the stage for revisiting dispersant preapproval in the California Current region. In addition, there is renewed local and national interest in reevaluating the use of chemical dispersants on oil slicks close to shore—0.5 nmi (California) or 3 nmi/60 ft isobath limit (other states). As noted above, most spills in the California Current states have been very close to shore. No authorization or preapproval exists for treating oil spills in-shore or over shallow water anywhere in the California Current region or the United States.

Preapproval is important because it ensures dispersion capability, training, and use in spill-response drills. Many response tools are preapproved and can be implemented by the FOSC without further consultation. But alternative tools, such as dispersants and burning, require the FOSC to first consult with the regional response team

(RRT), which includes representatives of all state and federal resource agencies and trustees.

To obtain approval or preapproval in the California Current states, the USCG must consult with state and federal wildlife and fisheries trustees on endangered species issues, managers of sanctuaries and reserves, and non-government organizations. Approval or preapproval must also satisfy requirements of federal essential fish habitat (EFH) regulations under the Magnuson-Stevens Act.

Scenarios for Ecological Risk Assessment

During 1998–2000 the USCG, together with several state agencies, hosted a series of ecological risk assessment (ERA) workshops (following Aurand 1995b) to evaluate and compare the benefits and risks of dispersing oil spills in nearshore and/or shallow-water areas. Work groups included resource trustee decision makers (risk managers) and resource scientists (risk assessors; Aurand et al. 2001). NOAA HazMat supported these workshops by providing model results for site-specific oil spill scenarios and other information needed to evaluate the effectiveness and effects of response operations.

In the California ERA workshops, risk managers decided on two worst-case scenarios, one off San Francisco in the Gulf of the Farallones and the other inside San Francisco Bay. In this paper, we highlight the "Pilot Station" spill located 6 nmi due west of the Golden Gate. It was decided by consensus that the scenario would involve release of 408,975 L (2,500 bbl¹) of a heavy fuel oil, IFO 180, at midnight in the fall season. Local conditions included constant northwesterly winds at 15 knots, 55° water temperature, and 1–2 foot waves (chop); the release was made during slack tide before ebb.

This scenario was significant because it occurred between the boundaries of two national marine sanctuaries (Gulf of the Farallones NMS and Monterey NMS) and had the potential to enter San Francisco Bay, exposing both bay and open coastal fisheries and wildlife resources to oil slicks, dispersed oil plumes, and/or smoke from in situ burning. In addition, late fall marks the Davidson Current season, which is characterized by a strong northward current which could move a dispersed oil plume up-coast and through the Gulf of the Farallones NMS.

The dispersion alternative was implemented at 1200 hrs, 12 hours after the spill, as the spreading slick was moving toward San Francisco and the Marin County shorelines. From this point forward two alternative scenarios were modeled over the next 3–4 days: the undispersed surface oil slicks moving toward and impacting San Francisco and Marin County shorelines, and the

¹ 1 barrel (bbl) = 42 gallons (US) = 159 L.

dispersed plume moving where currents dictated, northward along the coast to Point Reyes.

This spill scenario had an additional complication: the spilled oil, IFO 180, is a heavy fuel oil, which is, according to conventional wisdom, difficult to disperse. Laboratory and field tests, however, indicate that it is now possible to disperse this type of heavy fuel oil (Fiocco et al. 1999a). Accordingly, workshop participants wished to evaluate two dispersant effectiveness strategies: 35% effectiveness and 80% effectiveness.

Five response options were compared:

- No response: the oil was allowed to evaporate and disperse naturally and to strand on shore with no treatment or cleanup.
- Mechanical recovery: participants determined that 20% of the oil (500 bbls) could be removed from the sea surface by skimming, with cumulative removal rates of 250 bbls by hour 12, 425 bbls by hour 36, and 500 bbls by hour 72.
- Burning: participants determined that 280 bbls of floating oil could be boomed off and burned at hour 12.
- Dispersion at 35% and 80% effectiveness: participants determined that all necessary dispersant approvals were in place, delivery vessels and aircraft were properly equipped, and treatment with 2,400 gallons of dispersant mixture, at a dispersant-to-oil ratio of 1:20, could be executed over a five-hour period centered on hour 12.

SPILL SIMULATION METHODS

Two existing operational models and a simple box model were used to produce oil spill spreading and trajectory maps, charts of oil transformations, and concentrations of dispersed oil.

Oil Spill Spreading and Trajectory

We simulated the spreading, breakup, and trajectories of the oil spills with NOAA HazMat's On-Scene Spill Model (OSSM; Torgrimson 1984).² Inputs included maps, coastal outline and shoreline descriptors, bathymetry, numerical circulation models, statistical climatological simulations, location and type of the spilled substance, oceanographic and meteorological observations, and other data. Current speeds and directions were derived from tidal currents and current-meter records as modified by bathymetry. The output included time-series maps showing the overall size and shape of the oil

slick footprint, the concentrations of oil (percent cover) within the footprint, and their confidence limits.

Fate and Transformation

Oil properties (density, viscosity, volume, chemical composition) are rapidly transformed by spreading, evaporation, dispersion, emulsification, dissolution, oxidation, sedimentation, and biodegradation (collectively referred to as weathering). Oil decreases in mass and increases in viscosity because of evaporation and natural dispersion, and then increases in mass through the formation of water-in-oil emulsion (mousse). Transformation imposes increasing constraints on response. Viscous oil and mousse are difficult to disperse, difficult or impossible to skim without special equipment, and nearly impossible to burn.

Transformations of floating oil properties were computed by means of automated data inquiry for oil spills (ADIOS; Lehr et al. 1992). ADIOS integrates a library of approximately one thousand oils with a short-term oil fate and cleanup model to help estimate the amount of time that spilled oil will remain in the marine environment. The model output can be used to develop cleanup strategies. Input includes wind speed, salinity, water temperature, wave height, and type of oil. Output included a time series of means and confidence limits for viscosity, percent evaporation, water content, and natural dispersion. The volume of emulsion (mousse) was calculated as the sum of oil remaining plus its water content.

Dispersion Simulation

After the application of dispersants, oil droplets quickly mix down into the surface layer to a depth of 1.5 times the wave height (Delvigne and Sweeney 1988). The chemically dispersed oil droplets (smaller than about 60 microns) are neutrally buoyant and do not return to the surface. Wind causes Langmuir circulation (wind-generated convection cells found in the ocean that are responsible for vertical mixing down to a few tens of meters from the surface) and sets up circulation cells (tens to hundreds of meters apart) which move the neutrally buoyant droplets vertically, downward from the surface and stopping at the point in the water column where density increases rapidly (pycnocline; MacKay et al. 1982).

We simulated the dispersion of oil by using simple one-dimensional box modeling. The volume to be dispersed was determined by fate modeling (above) and by the ERA workshop managers' judgment on the effectiveness of a dispersant operation. During the first two hours after dispersion the volume of spilled oil was mixed vertically down to 1.0 m (1.5 times a wave height of 0.6 m defined by wind speed). Over the next 18 hours the dispersed oil was mathematically mixed down to the top of the pycnocline (7 m). The spreading and trajec-

²A recent update of the modeling system environment, "General NOAA Oilspill Modeling Environment" (GNOME) is given in Beegle-Krause 1999, and is also documented and available for use on our public Web site (<http://response.restoration.noaa.gov>). Recently, NOAA HazMat introduced ADIOS 2 (see detailed documentation and the model at the same Web site).

tory of the water mass containing dispersed oil was simulated with OSSM, but the wind was removed as a direct factor (the wind's indirect contribution to the current was retained).

Dispersed Oil Concentrations

We computed mean dispersed oil concentrations, in mg/L or parts per million (ppm), simply by dividing the dispersed oil volume (in liters or gallons) by the volume of water containing the dispersed oil (i.e., the product of the plume footprint area and its thickness). The calculation was performed for each of several time intervals (1, 2, 3, 4, 5, 6, 12, 18, 24, 36, 48, 72, and 96 hours). The result was a time series of mean dispersed oil concentrations that decrease continuously as the contaminated water volume increases.

Uncertainty

Several types of uncertainty were also addressed in the simulations. As noted above, uncertainties regarding the speed, spreading, and transport of undispersed surface slicks were defined by seasonal climatological variability and estimated errors in wind direction and speed (Galt 1997, 1998). The actual concentration of dispersed oil in the water column is also expected to have a large variability around the estimated mean concentration. The primary reasons for the variability are the patchiness of the surface oil distribution at the time of dispersant application, the uneven application of the chemical dispersant, and the spatial variations of the vertical mixing functions such as wind waves and Langmuir circulation. A variance of three around estimates of mean dispersed oil concentrations was suggested by MacKay et al. (1982) on the basis of a comparison of model results with actual data from intentional oiling field experiments in southern California. To account for all sources of variability and uncertainty, we computed upper dispersed oil concentrations as 5× the mean, and lower dispersed oil concentrations as 0.2× the mean. The range of dispersed oil concentrations represents our best professional judgment as to realistic oil concentrations on the basis of direct observation and other modeling activities related to dispersion processes.

Assessing the Ecological Effects of Dispersed Oil

The ERA workshop participants agreed that toxicity to marine fishes and invertebrates was their primary concern regarding the hazards associated with dispersing oil. There is a large body of data about the acute and chronic toxicity to adult and juvenile marine organisms of mechanically and chemically dispersed oil and dispersants. These data were presented to, and examined by, resource biologists during the course of the

TABLE 3
**Ranges of 96-Hour EC50s and LC50s for
 Early Life History Stages of 7 Species of Fishes and
 Invertebrates Subjected to Various Treatments**

Treatment	Type of exposure in ppm (mg/L)	
	Constant	Spiked
Corexit 9500	30–150	90–1,000
PBC: Prudhoe Bay crude oil	3–15	8–26
PBC + Corexit 9500	1–8	5–18
Arabian crude oil	0.6–6	15–80
Arabian + Corexit 9500	0.8–1.6	29–58
Venezuelan crude oil	0.2–0.4	1
Venezuelan + Corexit 9500	No data yet	No data yet

Source: data in CROSERF Progress Report, Coelho and Aurand (1999).

ERA workshops. The data were then used to develop consensus guidelines of concern.

Toxicity of dispersants and dispersed oil. Historically, oil toxicology data are largely based on 48- or 96-hour bioassays during which marine organisms are exposed to constant concentrations of dispersants, oil, or chemically dispersed oil. But in the ocean over a 48- or 96-hour time scale, dispersion causes constantly declining concentrations of oil. Fortunately, Singer et al. (1998), Rhoton et al. (1999), and Clark et al. (in press) have compared traditional constant-exposure with “spike” or “pulse” bioassays that attempt to mimic the concentration profile of dispersed oil during a chemical dispersion episode. The half-life of mean dispersed oil concentration in these spike exposures is about 2 hours. Results of the spike-exposure studies clearly indicate that zooplankton and early life stages of marine plants and animals are less sensitive to spiked exposures than to constant exposures (table 3). Therefore, in developing consensus guidelines for concentrations of concern, participating risk assessors considered both the spike-exposure data as well as the longer-term (96 h) “acute” toxicity data.

Consensus guidelines. Participants in each ERA workshop were polled to determine their levels of concern (discomfort level) about a range of exposure times and dispersed oil concentrations. Assessments were done separately for adult fish; adult crustaceans (shrimp, crab); and zooplankton and sensitive life stages of fish and crustaceans. In each workshop it was quickly agreed that the most sensitive forms were zooplankton and the early life stages of fishes and crustaceans. Also, the guidelines proposed independently in all three workshops were in remarkable agreement about concentrations and exposure times of concern (table 4).

For this paper, we apply these guidelines to the plume oil concentration data to determine what concentrations and exposure times are of concern.

TABLE 4
 Ecological Risk Assessment Workshop Participants' Levels of
 Concern for Various Marine Organisms during Exposure to Dispersed Oil

Exposure time (hours)	Concentration in ppm (mg/L)					
	Sensitive life stage ^a		Adult crustacean		Adult fish	
	High concern ^b	Medium concern	High concern	Medium concern	High concern	Medium concern
3	10	5	50	10	100	50
24	1	1	5	2	10	2
96	1		1	1	1	1
168	0.5	0.5	0.5	0.5	0.5	0.5

^aIncludes zooplankton as well as fish and invertebrate eggs and larvae.

^bConcern becomes medium or high when concentrations at time are exceeded.

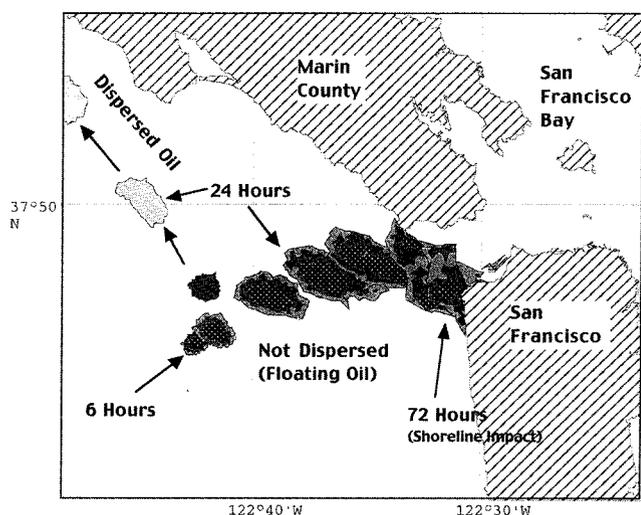


Figure 1. Trajectories and spreading of undispersed floating oil and dispersed oil plumes from Pilot Station scenario off San Francisco. Footprints are 6-hour intervals and then 12-hour intervals.

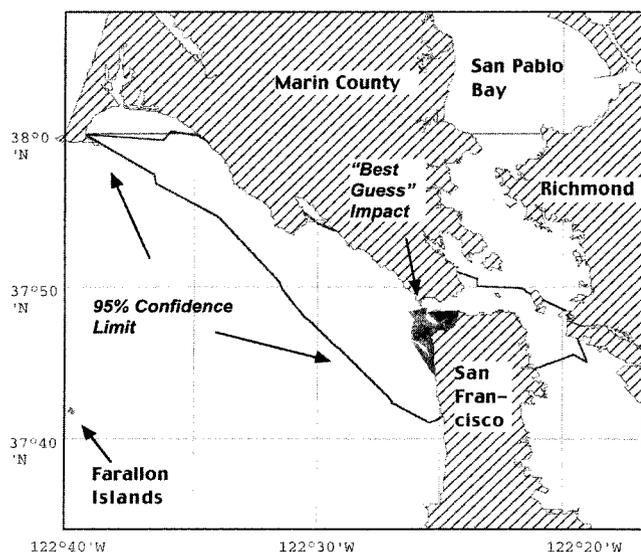


Figure 2. The 72-hour 95% confidence limits around floating (nondispersed) oil footprint following spill of 2,500 bbls of IFO 180 fuel oil at the San Francisco Pilot Station. We are 95% confident that oil will contact the shoreline within the boundaries of the drawn polygon.

SIMULATION RESULTS

The oil spill scenario at the San Francisco Pilot Station consisting of 2,500 bbls IFO 180 initially moved westward for several kilometers (0 to 6 hours), then turned to the northeast (6 to 12 hours) before moving rapidly eastward (fig. 1). Oiling of the San Francisco and Marin County shoreline began 60 to 72 hours after the spill, and then entered San Francisco Bay. The 95% confidence limits (fig. 2) indicate a chance of oil reaching the shoreline anywhere along the Marin County coastline as far north as Bolinas Lagoon, and extending south of San Francisco. The modeled oil spill produced oil slicks within boundaries of the Monterey Bay and Gulf of the Farallones National Marine Sanctuaries.

Fate and Transformation of the Five Response Options

The fate and transformation of the spilled oil was evaluated for five response options. Dispersants removed the greatest amount of oil, and the more effective dispersant level removed the most oil (fig. 3). Relative to the other options, dispersants substantially reduced the amount of both floating and stranded oil (fig. 3). Chemical dispersion also resulted in the lowest emulsion volumes compared with the other response options (fig. 4).

1. The **no response** option created a floating surface slick that was reduced from 2,500 to 1,975 bbls during the first 48 hours by evaporation (479 bbls) and natural dispersion (46 bbls, fig. 3a). By 72 hours, 770 bbls of oil were stranded on shorelines, reducing the floating oil to 1,125 bbls. At the end of 96 hours 979 bbls of oil remained floating, 883 bbls were stranded on beaches, 561 bbls evaporated, and 77 bbls dispersed naturally. Over 3,700 bbls of emulsion had formed by 72 hours (fig. 4a).
2. The **mechanical response** (skimming) option began six hours after the spill (fig. 3b). The amount of oil removed by mechanical response ranged from about 75 to 200 bbls per day through 96 hours, resulting in

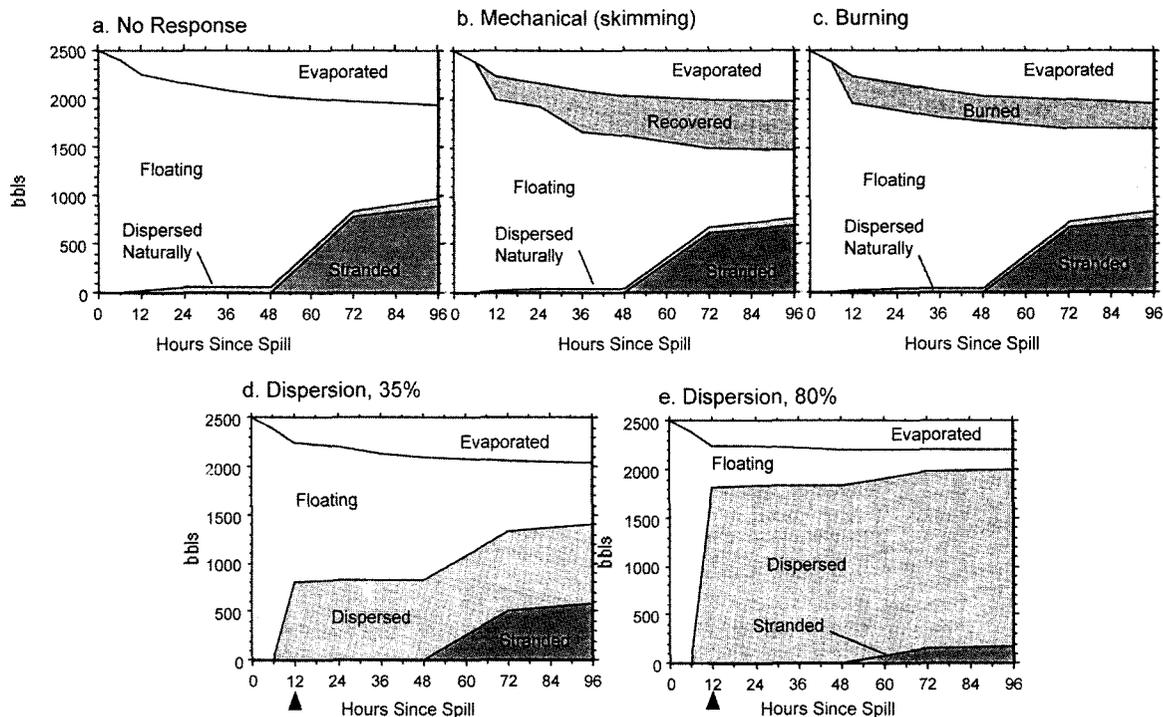


Figure 3. Fates of 2,500 barrels of IFO 180 oil spilled at Pilot Station off San Francisco when subjected to five response alternatives: a, no response; b, mechanical removal (skimming); c, in-situ burning; d, dispersion of 35% of the oil, and e, dispersion of 80% of the oil. Units are volumes in barrels (bbls; 1 bbl = 42 gal). Each panel shows how much oil was evaporated, removed (only by mechanical means and burning), dispersed, and stranded on shorelines.

a total recovery of 500 bbls of oil. Relative to the no response alternative, mechanical recovery slightly reduced the amount of oil stranding on shorelines, to 700 bbls, and it reduced the amount of naturally dispersed oil from 77 to 68 bbls. The amount of oil remaining on the sea surface at 96 hours was 720 bbls.

3. The **burning response** option occurred at 12 hours, removing 280 bbls of floating oil (fig. 3c). This action had less of an effect on the subsequent fate and transformations of the oil than did the mechanical response. For example, after 96 hours (84 hours after burning) 772 bbls of oil were stranded on shore and 856 bbls of oil were floating.
- 4-5. The **dispersion response** scenarios at the 35% and 80% levels of effectiveness 12 hours after the spill removed 790 and 1,805 bbls, respectively, into the water column (fig. 3d, e). Oil not removed or dispersed began to absorb water and emulsify after 48 hours, resulting in rapidly increasing volumes of emulsion. The 80% dispersion alternative resulted in a floating emulsion volume of 500 bbls (fig. 4b) and a stranded emulsion volume of about 300 bbls (fig. 4c).

Dispersion stopped the oil's eastern trajectory and placed it into the northerly-moving currents (figs. 1 and 5). From this point forward the dispersed plume would move north parallel to shore and generally

above the 40 to 60 m isobath. The plume would round Point Reyes between 48 and 72 hours after dispersion, then continue moving north (fig. 5) and diluting (fig. 6a). After dispersion (12 hours) the plume would reach a maximum (assigned) pycnocline depth of 7 meters, some 30-50 m above the seafloor (fig. 6b).

Dispersed Plume Oil Concentrations

Dispersed oil plume concentrations were analyzed for both dispersion effectiveness concentrations, but not for the other response options. The mean concentrations of dispersed oil are shown, for both the 35% and 80% dispersion effectiveness scenarios, on the map in figure 5, and as time-series graphs in figures 6, 7, and 8. Upper and lower confidence limits (for the 35% effectiveness scenario only) are shown in figure 6a. Within the plume resulting from 35% dispersion, the mean dispersed oil concentrations dropped from a first-hour peak of 272 ppm (ml/L) to about 0.3 to 0.4 ppm (figs. 5, 6a, and 7a). After rounding Point Reyes the mean plume concentration would decrease slowly from 0.3 to <0.1 ppm. If dispersion were 80% effective, the oil concentrations would range from 622 ppm at the first hour to 0.8 ppm in transit from the dispersion site to Point Reyes, and then to less than 0.1 ppm as the plume traveled farther north (fig. 5).

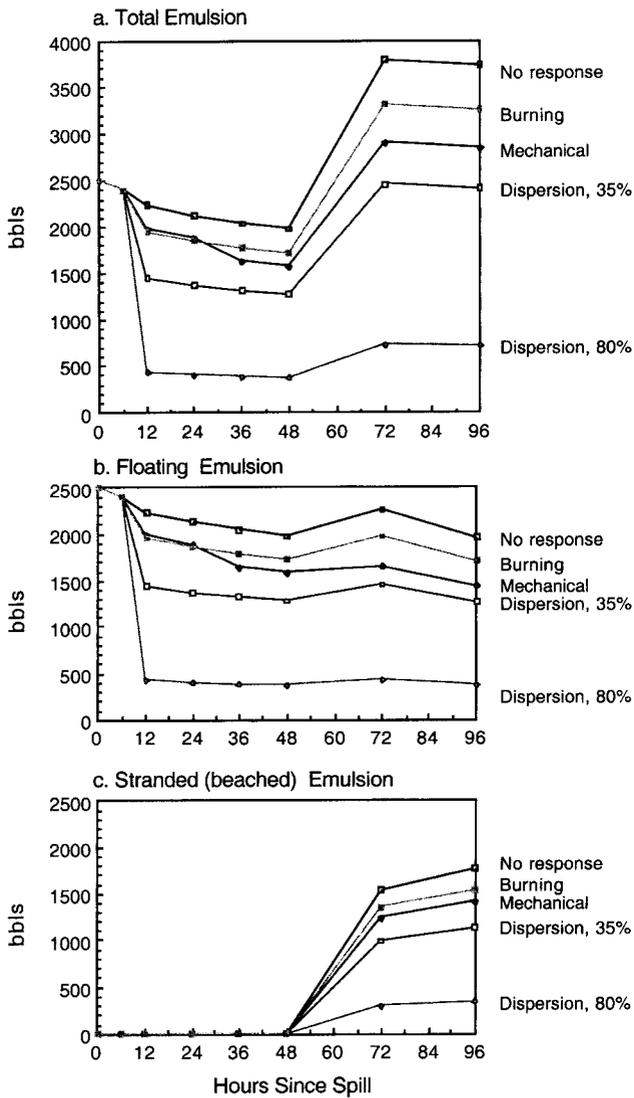


Figure 4. Changes in volumes of water-in-oil emulsion of 2,500 bbls of IFO 180 oil spilled at Pilot Station off San Francisco and subjected to five response alternatives: a, total emulsion; b, floating emulsion; and c, emulsion stranded on shorelines (beached). Each panel shows emulsion volumes resulting from each of the five response scenarios.

Consensus Guidelines on Oil Toxicity

Dispersed oil toxicity differed between the two levels of dispersion effectiveness. At 35% dispersion effectiveness, the consensus guideline of medium concern for adult fish (50 ppm during the first 3 hours and 10 ppm at 24 hours) was exceeded by mean dispersed oil concentrations during the first 6 hours but not thereafter (fig. 7a). This means that there was a chance that some adult fish in the upper meter, such as herring, forage fish, or salmon, were exposed to a concentration of medium concern to the risk assessors for less than six hours.

The consensus guideline of medium concern for adult crustacea (crabs, shrimp; 10 ppm during the first three hours and 2 ppm by 24 hours) was exceeded by the

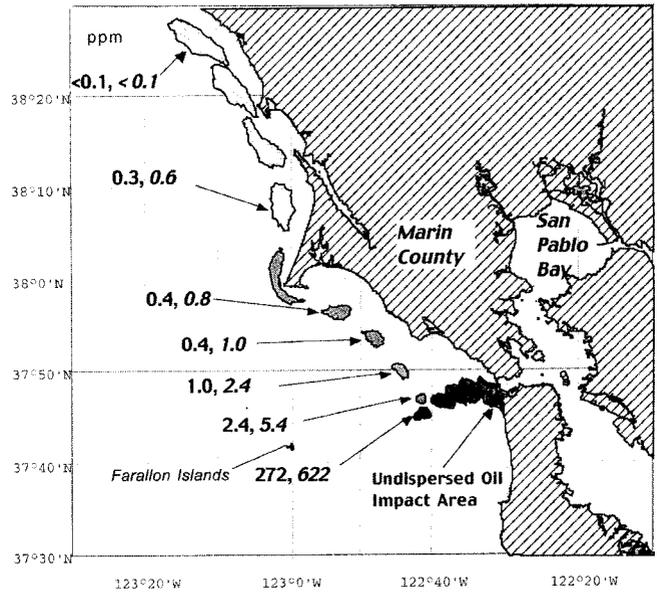


Figure 5. Mean concentrations (ppm) of oil in 35% effectiveness (bold) and 80% effectiveness (italic) dispersed plume, starting 1 hour after dispersion, as it moved northward over 96 hours.

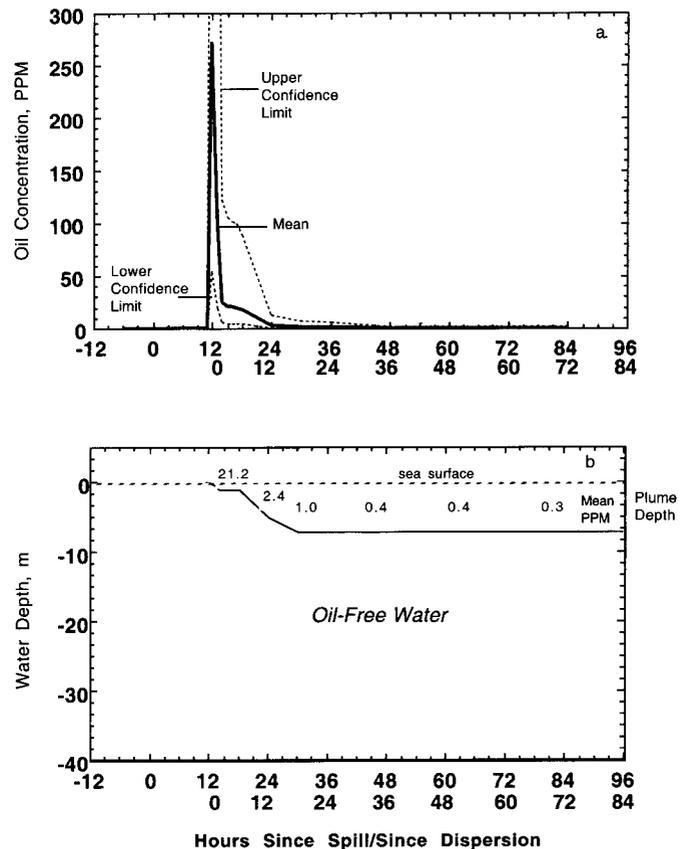


Figure 6. Comparison of 35% effectiveness dispersed oil concentration time series with dispersed plume depth and bottom depth along the plume trajectory. Dashed lines in a are upper and lower confidence limits; solid line is the mean (based on dispersion of 790 bbls). b. A temporal cross-section along the dispersed plume path over bottom depths of 40 meters or deeper.

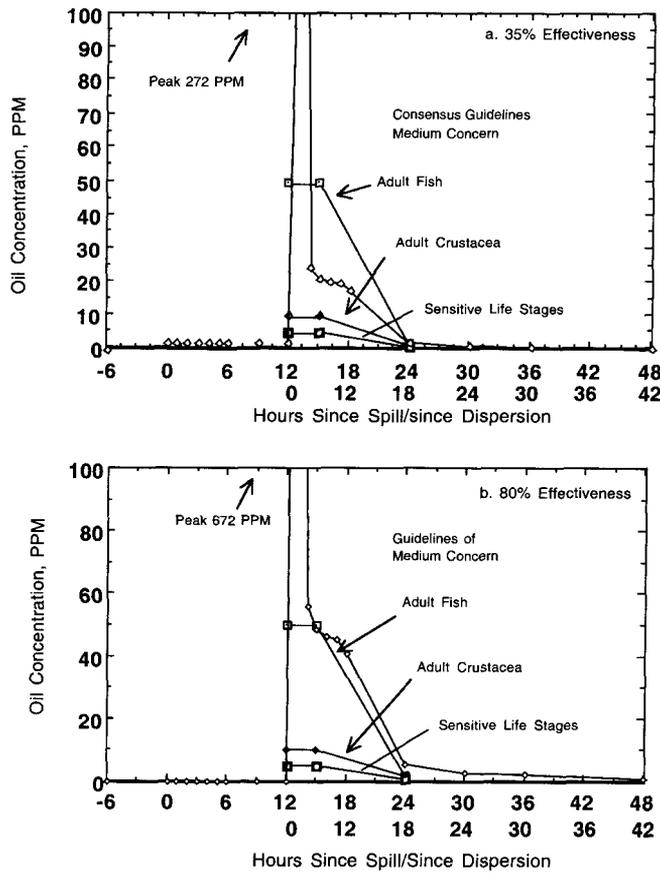


Figure 7. Time series of mean plume concentrations of dispersed oil plotted over consensus concentrations of medium concern to ERA workshop risk assessors. Plots are for two levels of dispersion effectiveness: a, 35%, or 790 bbls dispersed, and b, 80%, or 1,805 bbls dispersed.

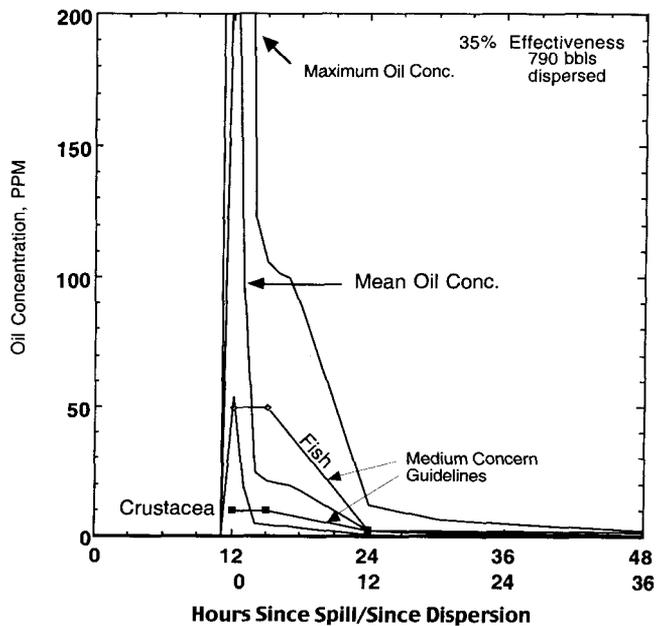


Figure 8. Close-up view of mean and maximum plume concentrations of dispersed oil from 35% effectiveness treatment, plotted over consensus concentrations of medium concern to ERA workshop risk assessors.

mean plume concentration for the first 12 hours after application of dispersants. Over this period the oil was mixing from one to three meters deep. This means that there was a chance that shrimp or crab in the upper several meters of the water column were, for up to 12 hours, at risk of exposure to a concentration of medium concern to the risk managers. However, from about 12 hours onward, dispersed oil concentrations fell below this level of concern.

The consensus guideline of medium concern for zooplankton and early life stages of fishes and invertebrates (5 ppm during the first 3 hours) was also exceeded by the mean concentration during the first 12 hours after application of dispersants (fig. 7a). These observations indicate that zooplankton, including fish and invertebrate eggs and larvae, in the upper three meters of the water column were exposed to oil concentrations at or above the medium concern level of the risk assessors.

The foregoing presentation focused on mean concentrations. Within a dispersed plume, oil is not uniformly distributed. There will be patches of dispersed oil with concentrations that range from as high as five times the mean to one-fifth the mean, indicating that a small fraction of the biota in the upper water column will be exposed to oil in concentrations and durations that exceed the consensus guidelines. Figure 8 presents a “close-up” view showing the maximum expected concentrations and the extent to which they exceed the consensus guidelines of medium concern. Further, at 80% dispersion effectiveness (over 1,800 bbls dispersed) all concentrations would be proportionately higher and would exceed the consensus guidelines longer than at 35% dispersion effectiveness (fig. 7b).

DISCUSSION

Ecological Considerations

The ecological and fisheries trade-offs of the dispersant simulation are clear (Kraly et al. 2001). On one hand, dispersion affects plankton and early life stages of fish in several square kilometers of water during the first day after dispersion. Alternatively, not dispersing or otherwise removing large quantities of surface oil results several days later in the oiling of seabirds and the shoreline occupied by shorebirds and beach-spawning forage fishes.

Dispersing crude oil in the Gulf of the Farallones resulted in a several-square-kilometer area of oil mixed in the upper 3 meters of water. The concentrations of oil 1 hour after dispersion ranged from 200 to 600 ppm, and declined rapidly to 0.5–5 ppm 12 to 24 hours after dispersion. Under consensus guidelines, exposure concentrations and times within the plume would be of medium to high concern to risk assessors for plankton, fish eggs, and fish larvae, but of much less concern with

respect to adult crustaceans. Adult fish were exposed to oil concentrations of medium concern only during the first 2 hours after dispersion. If dispersion was 85% effective, the shorelines of San Francisco and southern Marin County, and resident shorebirds, would have been spared a considerable amount of oiling from emulsion (mousse). The main body of dispersed oil would have moved offshore to the north. If dispersion was only 35% effective, oiling of shoreline and birds would have been proportionately greater.

Under the no response, mechanical recovery, and burning scenarios, floating oil would have continued to disperse slightly, emulsify, increase in volume, and increase in viscosity, making open-water mechanical recovery difficult, and subsequent dispersion or burning nearly impossible. Seabirds foraging from the Farallon Islands and the mainland would have been oiled and in need of rehabilitation. The oil that would strand on shorelines would be emulsion (mousse). It would have come ashore as brown, sticky mats, stranding along the high-tide line on sand and gravel beaches, and could impair the reproduction of shore-spawning fishes. If temperatures rose, the stranded mousse would become less viscous, and then penetrate into the sand and gravel. Residual oil would remain in the gravel after manual cleanup unless methods such as berm relocation or surf washing were used. Heroic methods would also damage the eggs of beach-spawning fishes and invertebrates and, ironically, disperse oil into the very shallow nearshore zone occupied by algae, seagrasses, crabs, and juvenile fishes such as Pacific herring (*Clupea harengus harengus*), rockfishes (*Sebastes* spp.) and salmonids. Residual oil might be present for years, depending on wave exposure. We estimated the amounts of emulsion stranding on shorelines, but not lengths of shoreline affected, or numbers and kinds of seabirds at risk from oiling, which are topics worthy of further analysis.

Limitations

In this part of the ERA analysis, the only biological response that was simulated was immediate death; we did not attempt to account for sublethal toxic effects. Adult salmon have a low mortality risk because of their ability to detect and avoid dispersed oil (Green et al. 1982; Nakatani and Nevissi 1991). Alternatively, shellfish such as oysters and clams can temporarily bioaccumulate (and then depurate) dispersed oil (Michel and Henry 1997), which could lead to temporary closures of shellfish fisheries.

The scenarios and workshop proceedings were based on the results of models, not oil spills. In Europe, experience in dispersing real spills was gained during the large nearshore *Sea Empress* spill in Wales (Lunel 1998).

Additionally, numerous sea trials in the North Sea have tested dispersion technology and provided new data to resolve uncertainties in models (Lunel et al. 1997) and give clearer guidance for dispersant operations (Lunel and Lewis 1999). In comparison to sea trials testing dispersants and dispersant use in real oil spills, we believe our dispersion simulation is extremely conservative, overestimating both oil concentrations and duration.

The scenarios modeled were conservative in terms of the effectiveness of dispersant application, and in terms of the scales and amounts of oil that can actually be dispersed. The ranges of effectiveness used here, 35%–80%, are realistic, especially for medium crude oils, and are considerably higher than for mechanical removal (booms and skimmers) at sea states and wind conditions typical of the California Current. The main benefit of dispersion was the reduction (not elimination) of floating surface oil and quantity of emulsified oil.

One final caveat is that this modeling exercise did not account for the long-term fate of dispersed oil. Entrainment in the planktonic food web and enhanced biodegradation via the microbial and planktonic food web (Swannel and Daniel 1999) are distinct possibilities.

Recommendations

The consensus guidelines offered by ERA workshop facilitators and participants (table 4) make effective use of existing toxicity data. But we urge that the consensus guidelines be revisited and further reviewed as new data become available.

The granting of preapproval to use dispersant in response to oil spills requires input from regulators and the public. If preapproval cannot be granted, managers and responders should at least consider dispersion as an option during future spills, call for modeling if appropriate, and include dispersion as an option in future spill drills. Because this scenario was modeled for late fall conditions, future nearshore modeling scenarios should be conducted for late winter and spring, when the early life stages of California Current nearshore fishes are present (e.g., Watson et al. 1999).

The model results need further validation through comparison to oil concentrations and durations achieved when dispersants are applied to real oil spills. There is great need for high-quality monitoring data to verify modeling and to confirm the effectiveness and biological effects of dispersant operations. A modified fluorimetry system and protocol is available and in use by the USCG for rapid response monitoring of dispersion effectiveness (Henry et al. 1999). The use of fluorimetry and pertinent visual observations (Levine 1999), coupled with modeling, would provide valuable new information and allow for better planning simulations.

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Part III

SCIENTIFIC CONTRIBUTIONS

THE CALCOFI ICHTHYOPLANKTON TIME SERIES: POTENTIAL CONTRIBUTIONS TO THE MANAGEMENT OF ROCKY-SHORE FISHES

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ABSTRACT

Harvest of nearshore fishes off California, particularly species in the recently expanded live-fish fishery, has impacted many of these stocks. Important taxa are cabezon, sheephead, lingcod, greenlings, and the rockfishes included in the subgenus *Pteropodus*. Life-history information and fishery-independent abundance indices are badly needed for the development of management strategies for these stocks. The California Cooperative Oceanic Fisheries Investigations (CalCOFI) surveys can provide indices of abundance for larval stages of many species, including cabezon, sheephead, kelp and sand basses, lingcod, and several species of rockfishes. This paper presents, as examples, data on the distribution and abundance of cabezon, sheephead, and *Paralabrax* (kelp and sand bass) larvae in the Southern California Bight region and compares these with data from other nearshore ichthyoplankton surveys conducted in the region. Trends in landings for cabezon generally match trends in CalCOFI larval indices, supporting use of the larval catch data as fishery-independent abundance indices. The principal recommendation for improving nearshore larval time series is to reestablish plankton tow stations on CalCOFI survey cruises off central California, where standard plankton tows have not been taken since the survey area was reduced in 1985.

INTRODUCTION

The decline of West Coast rockfish (*Sebastes*) populations over the past several decades has left many stocks at dangerously low levels (Ralston 1998). Nowhere is this more evident than in the California trawl fishery, once dominated by bocaccio (*S. paucispinis*), a species that now is in rebuilding status (Ralston et al. 1996; MacCall et al. 1999). The contribution of recreational fisheries to the present condition of rockfish stocks is demonstrated by the severely depleted cowcod (*S. levis*), a species highly prized by both commercial and recreational fisheries. It, too, is in rebuilding status and has become a foundation species for new protective regulations in rockfish management (Butler et al. 1999). During

the past decade, the growing popularity of the live-fish restaurant trade has produced a highly focused nearshore fishery that targets rockfishes of the subgenus *Pteropodus* (e.g., copper, grass, gopher, brown, and kelp rockfishes) and other associated shallow-water reef fishes (e.g., cabezon, greenlings, lingcod, sheephead). The impact of this fishery is superimposed on long-standing commercial and recreational fisheries for these species. Harvest of these nearshore stocks has progressed at a rate that may place them in the same status as those in deeper-water habitats (Pattison and Vejar 2000). Other key species in the nearshore environment are kelp and barred sand bass (*Paralabrax clathratus* and *P. nebulifer*), nonmarket species that have been mainstays of private and commercial sport fisheries in southern California.

The state of California has new responsibilities to manage and conserve nearshore fish species and their habitats. Among the most valuable assets for such stock assessments are long-term fishery-independent indices that originate well before the expansion of the fisheries and encompass the major shifts in ocean climate associated with the history of the fishery. The 51-year-long ichthyoplankton time series from the California Cooperative Oceanic Fisheries Investigations (CalCOFI) surveys provides such indices of abundance for larval stages of many species.

Although a primary objective of CalCOFI was to determine the cause for the decline of the Pacific sardine (*Sardinops sagax*) in the middle of the last century, CalCOFI data have been central to our understanding of population processes of a large array of marine organisms, from phytoplankton to mammals. CalCOFI has played an important role in the successful management of northern anchovy (Smith 1972; Lasker 1985) and Pacific sardine, which has rebounded dramatically during the past 20 years (Wolf 1992; Hill et al. 1999). Although CalCOFI surveys were designed to encompass the widespread open-ocean spawning of Pacific sardine, it is a surprising fact that trends in larval abundance of nearshore species in CalCOFI collections usually track changes in abundance of adults quite well, even when a species is greatly undersampled due to the offshore emphasis of the CalCOFI sampling pattern (Ralston et al. 1996;

Butler et al. 1999). In addition to indices of larval abundance, the CalCOFI ichthyoplankton time series can provide valuable information on spawning seasons and temperatures as well as larval dispersion and mortality.

The objectives of this paper are to present current and potential contributions of the CalCOFI ichthyoplankton time series to nearshore fish management and ecology, and to compare CalCOFI larval indices with other available larval fish time series for this region. We examine trends in larval abundance of cabezon and sheephead, two important species currently under exploitation by the live-fish fishery, and kelp and barred sand bass, important nonmarket sport fishes, and then compare these with trends in the Southern California Bight (SCB) time series of the Natural History Museum of Los Angeles County (LACM) and MEC Analytical Systems (MEC), and with trends at Diablo Canyon off central California, monitored by Tenera Environmental Services (Tenera). Lastly, we consider how nearshore surveys could be augmented to produce more useful indices, and we discuss more costly methodologies, such as larval and egg production estimation techniques, that could provide direct measures of absolute fish abundance.

METHODS

Initially, CalCOFI conducted monthly surveys over a large portion of the California Current region from northern California to the tip of Baja California, Mexico—the spawning range of the Pacific sardine during the first decade of the CalCOFI program (see survey map on the inside back cover of this volume). Areal and temporal coverage contracted over subsequent decades; since 1985, the surveys have been limited to a pattern of 66 stations in the SCB region (Hewitt 1988; Moser et al. 1993, 1994). The Southern California Bight has been the most frequently occupied region of the overall CalCOFI survey pattern.

The oblique net tow time series for the species treated in this paper comprises 11,924 tows taken on 243 cruises during 1951–2000 within the boundaries of the present CalCOFI survey. These include all standard oblique CalCOFI survey tows taken since 1985, when occupancy of the present pattern was initiated. Oblique tows used prior to 1985 are a subset from the wider-ranging CalCOFI surveys (Hewitt 1988; Moser et al. 1993, 1994). On surveys prior to 1985 in the Southern California Bight, nearshore stations did not always correspond to the exact positions of the 66 nominal stations used on surveys since 1985. In order to expedite the construction of distribution maps, we assigned data for stations other than the nominal stations of the present pattern to the closest of the 66 nominal stations. Calculations for occurrence (proportion of positive tows) and abundance (larvae per 10 m² surface area) were consistent

with procedures used in Moser et al. 2001. For these calculations, station 60 on each of the current CalCOFI lines defines the outer margin of the continental borderland and the Southern California Bight region; the SCB region includes line 77 (fig. 1), even though that line is north of Point Conception. Station 70 was used as the outer boundary for calculating occurrence of cabezon larvae because they were distributed farther offshore than sheephead and *Paralabrax* spp. larvae (Moser et al. 2001).

The basic plankton tow methodology for oblique tows and sample handling were consistent throughout the time series (Kramer et al. 1972; Smith and Richardson 1977; Moser et al. 1993, 1994). Neuston tows have been taken at each station on all CalCOFI survey cruises since 1978 with a manta net (Brown and Cheng 1981; Moser, Charter, Reilly et al. 2000). Hauls were made at a ship speed of 1.0–2.0 knots for 15 minutes, except in 1978 when tow duration was 3 minutes. The manta net time series for the species in this paper includes 4,733 tows taken on 88 cruises.

Data were available from LACM and MEC surveys, conducted over shelf areas of the SCB in the years between 1978 and 1986, and from Tenera surveys conducted at the Diablo Canyon power plant in central California from 1990 to the present. With minor exceptions, gear and tow methodology used by LACM, MEC, and Tenera were similar to those of CalCOFI. The MEC oblique tows were taken in 30-second steps, but equivalent volumes of water were filtered for all portions of the water column. Surface tows taken by Tenera within the intake bay at Diablo Canyon employed a 0.5 m ring net towed just below the surface on the same transect on a weekly basis.¹

RESULTS

Demersal Habitats in the SCB

The inner third of the present CalCOFI survey pattern overlies the continental borderland of southern California, a region of complex topography that includes the mainland continental shelf and slope, deep-water basins, and numerous islands and banks and their shelves and slopes (fig. 1). The islands and banks extend coastal habitats >100 nmi offshore, and the basins provide deep-water habitats and zoogeographic refugia for many mid-water species. Point Conception forms the zoogeographic boundary between the Oregonian shore fauna to the north and the San Diegan fauna, which extends southward to about Magdalena Bay, Baja California Sur,

¹Tenera Environmental Services. 2000. Diablo Canyon Power Plant, 316(b) demonstration report. Prepared for Pacific Gas and Electric Company. San Francisco, Calif.

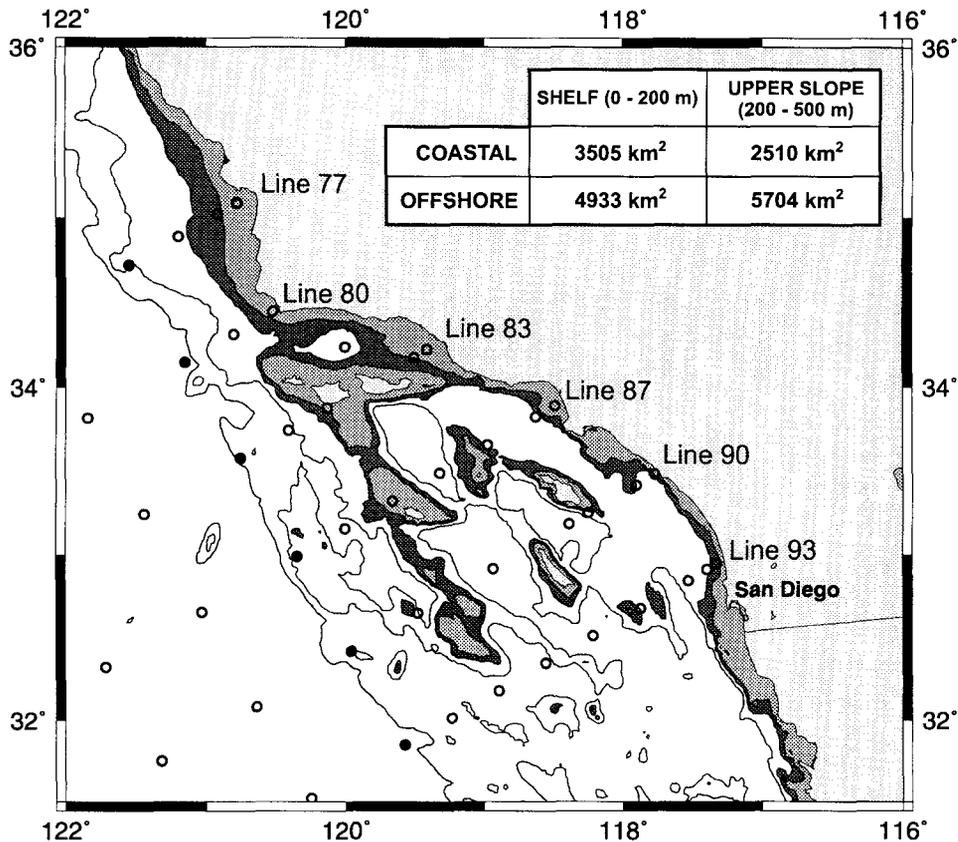


Figure 1. Bathymetry of the nearshore part of the current CalCOFI survey pattern, showing total bottom areas of shelf and upper slope for the region within the Southern California Bight. Shelf (0–200 m), medium shading; upper slope (200–500 m), dark shading; deeper isobaths, 1,000 m and 2,000 m. Station locations are shown as circles; on each survey line station 60 is denoted by a filled circle.

Mexico. The offshore region of the continental borderland has 40% more shelf habitat and more than twice as much upper slope habitat than the mainland coast (fig. 1). The Santa Rosa–Cortez Ridge represents essentially a second coastline equivalent in shelf and slope area to the mainland coast. Because of this, most CalCOFI stations in the SCB, out to station 60, are near sources of rocky-shore fish larvae (fig. 1). Although only ~30% of the stations in the present survey pattern are over or adjacent to the continental shelf or upper slope, the circulation pattern over the SCB (see below) favors the dispersal of larvae from nearshore habitats to regions well seaward of their origins.

The topographic complexity of the continental borderland is matched by its complex hydrography. The coastal jet of the California Current courses equatorward along the central California coast, sweeps around Point Conception, and continues along the outer margin of the continental borderland; a coastward branch of the current turns poleward to form the Southern California Eddy, centered on the outer Channel Islands (Lynn and Simpson 1987). The inshore poleward component of the eddy circulation is augmented seasonally

and episodically by the Inshore Countercurrent flowing from Baja California. Another major feature is the extensive undercurrent that flows poleward at slope depths over the borderland (Lynn and Simpson 1990). Surface waters overlying the continental borderland are richer than the relatively more oligotrophic offshore waters as a result of seasonal coastal upwelling and the complex pattern of mesoscale circulation (Hayward and Venrick 1998). Three oceanic water masses (Subarctic, Pacific Central, and equatorial water of the eastern tropical Pacific) converge in the SCB region, where complexity is heightened by a field of mesoscale eddies that extends from the inner margin of the California Current into the SCB, and by a persistent frontal zone (Ensenada Front) at the southwest corner of the bight (Lynn and Simpson 1987; Haury et al. 1993).

Rocky-Shore Species in the CalCOFI Time Series

The larvae of rocky-shore fishes are an important, although not numerically dominant, part of the ichthyoplankton in CalCOFI samples. In oblique plankton tows, coastal pelagic fish larvae are the dominant cate-

TABLE 1
Taxonomic Composition and Relative Abundance (Percentage of Total Abundance) of Larval Fish Categories in CalCOFI and LACM Time Series in the Southern California Bight Region

Habitat	CalCOFI		LACM	
	Taxonomic composition (%)	Relative abundance (%)	Taxonomic composition (%)	Relative abundance (%)
Coastal pelagic	4.4	69.7	8.5	72.4
Other pelagic	6.7	0.2	0	0
Midwater	37.7	20.5	10.6	1.4
Rocky substrate	26.3	7.4	45.1	3.5
Soft substrate	24.9	2.2	35.9	22.7

TABLE 2
Larvae of Rocky-Shore Fish Taxa* Identified in CalCOFI Oblique Tow Samples in the Southern California Bight Region, by Overall Abundance

Common name	Scientific name	Rank	Time series
Fisheries species			
Bocaccio	<i>Sebastes paucispinis</i>	22	1951–2000
Cowcod	<i>Sebastes levis</i>	97	1951–2000
Aurora rockfish	<i>Sebastes aurora</i>	47	1951–2000
Kelp and sand bass	<i>Paralabrax</i> spp.	49	1951–2000
Pacific barracuda	<i>Sphyræna argentea</i>	55	1951–2000
Chilipepper	<i>Sebastes goodei</i>	66	1951–1969
Cabezon	<i>Scorpaenichthys marmoratus</i>	86	1951–2000
Sheephead	<i>Semicossyphus pulcher</i>	112	1961–2000
Lingcod	<i>Ophiodon elongatus</i>	184	1951–2000
Other species			
Shortbelly rockfish	<i>Sebastes jordani</i>	9	1951–2000
Señorita	<i>Oxyjulis californica</i>	38	1961–2000
Blacksmith	<i>Chromis punctipinnis</i>	48	1951–2000
Blackeye goby	<i>Coryphopterus nicholsii</i>	68	1985–2000
Mussel blenny	<i>Hypsoblennius jenkinsi</i>	84	1985–2000
Garibaldi	<i>Hypsypops rubicundus</i>	90	1957–2000
Red brotula	<i>Brosomphycis marginata</i>	95	1951–2000
Roughcheek sculpin	<i>Ruscarius creaseri</i>	105	1985–2000
Painted greenling	<i>Oxylebius pictus</i>	107	1951–2000
Rubynose brotula	<i>Catactyx rubrirostris</i>	129	1985–2000
Bluebanded goby	<i>Lythrypnus dalli</i>	136	1985–2000
Halfmoon	<i>Medialuna californiensis</i>	142	1951–2000
Opaleye	<i>Girella nigricans</i>	146	1951–2000
Deepwater kelpfish	<i>Cryptotrema corallinum</i>	151	1985–2000
Zebra goby	<i>Lythrypnus zebra</i>	158	1985–2000
Blind goby	<i>Typhlogobius californiensis</i>	159	1985–2000
Smoothhead sculpin	<i>Artedius lateralis</i>	160	1985–2000
Rock wrasse	<i>Halichoeres semicinctus</i>	168	1961–2000
Bay blenny	<i>Hypsoblennius genivittatus</i>	173	1985–2000
Yellowfin fringehead	<i>Neodilinus stephensae</i>	175	1985–2000
Rough ronquil	<i>Rathbunella alleni</i>	177	1985–2000
Salema	<i>Xenistius californiensis</i>	181	1985–2000
Scalyhead sculpin	<i>Artedius harringtoni</i>	189	1985–2000
Slimy snailfish	<i>Liparis mucosus</i>	190	1985–2000
Padded sculpin	<i>Artedius fenestralis</i>	192	1985–2000

*Limited to taxa with 100 or more total larvae (larvae per 10 m², summed over the time series).

gory, with about 70% of total larvae contributed by only 4% of the total taxa (table 1). Midwater fish larvae have the most taxa (38%) and are second in abundance, with 20% of the total larvae. Rocky-shore fishes contribute about 1/4 of the taxa but represent only 7% of the total larval abundance. In the LACM nearshore larval surveys, bottom fish taxa constitute ~80% of the total taxa (nearly

half the total are rocky-substrate taxa) and, as expected, the larvae of midwater species represent only 11% of the total taxa and ~1% of the total larval abundance. As in the CalCOFI surveys, larvae of coastal pelagic fishes dominate the LACM surveys with >70% of the total abundance contributed by 8.5% of the taxa (table 1). In the LACM surveys, larvae of soft-substrate fishes are ten times more abundant than in CalCOFI surveys.

Although few of the *Sebastes* larvae taken in CalCOFI samples are identifiable to species, some important species can be identified (table 2). Four of these (bocaccio, cowcod, aurora rockfish, and chilipepper) are heavily exploited. Shortbelly rockfish has the potential to be an important fishery because of a large biomass that may approach a half-million tons (Pearson et al. 1991). Larvae of lingcod, a heavily impacted species, are neustonic and thus not abundant in CalCOFI oblique tows; however, they are a prominent species in CalCOFI manta tows. Pacific barracuda is an important species in recreational fisheries and, as a voracious fish predator, plays an important ecological role in the nearshore habitat. Its larvae are moderately abundant in CalCOFI oblique tows. Although larvae of kelp bass (*Paralabrax clathratus*) and barred sand bass (*P. nebulifer*) are not identifiable to species, the time series representing them in aggregate (*Paralabrax* spp.) may prove to be a useful index. Larvae of spotted sand bass (*P. maculatofasciatus*) are not differentiable from the other two *Paralabrax* species, but it is unlikely that they are present in CalCOFI samples because they are primarily bay inhabitants. Cabezon and sheephead are important species in nearshore fisheries and are well represented in the CalCOFI time series as well as in the nearshore time series. Abundance trends for larvae of cabezon, sheephead, and *Paralabrax* spp. are described below.

Cabezon. Cabezon are exploited in all nearshore fisheries. The most consistent record is from the commercial passenger fishing vessel (CPFV) catch, beginning in 1936 (fig. 2). Cabezon catch rose rapidly after WWII to a peak in 1956 and then showed a trend of irregular decline. Catch was distinctly seasonal, with a minimum during winter months and then a steady increase to a summer peak.

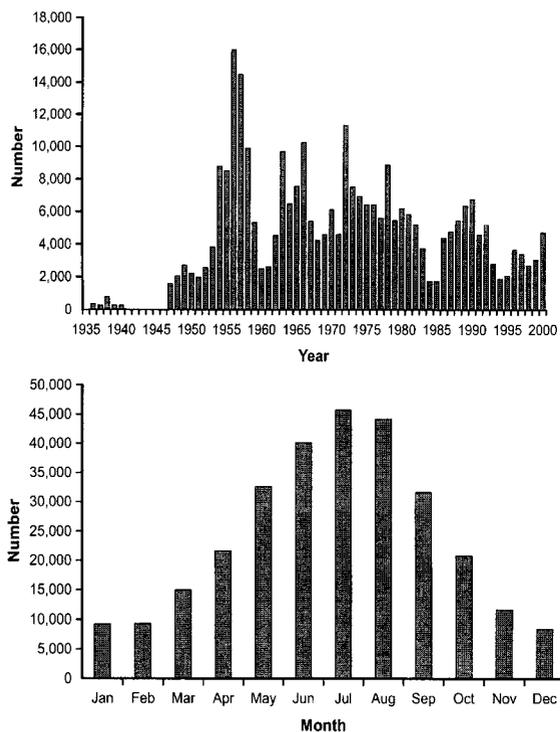


Figure 2. Total catch (numbers of fish) of cabezon from commercial passenger fishing vessels off California by year (above) and month (below); from database described in Hill and Schneider 1999.

Highest average abundance of cabezon larvae in oblique tows is at CalCOFI survey stations north of Point Conception and in the northern sector of the SCB (fig. 3). This reflects the more northerly distribution of this wide-ranging (central Baja California to southeast Alaska) species, whose population center appears to be off northern California (O'Connell 1953; Doyle 1992a, b; Moser et al. 1993). Although highest average abundances were at stations over the shelf or upper slope, about half of the positive stations were over deep water (fig. 3). Abundance was relatively high at stations well offshore of Point Conception, and transport of cabezon larvae into the SCB from the north probably is affected by variation in the speed and degree of offshore divergence of the California Current in the Point Conception region. The pattern of distribution and abundance of cabezon larvae in manta tows in the SCB was similar to the pattern for oblique tows, except that average abundance was approximately five times higher in manta samples (fig. 4). In contrast to oblique tows, average abundance in manta tows was consistently as high at stations in the northern sector of the SCB as at stations north of Point Conception.

Time series of occurrence of cabezon larvae in oblique tows show a generally decreasing trend since the 1950s,

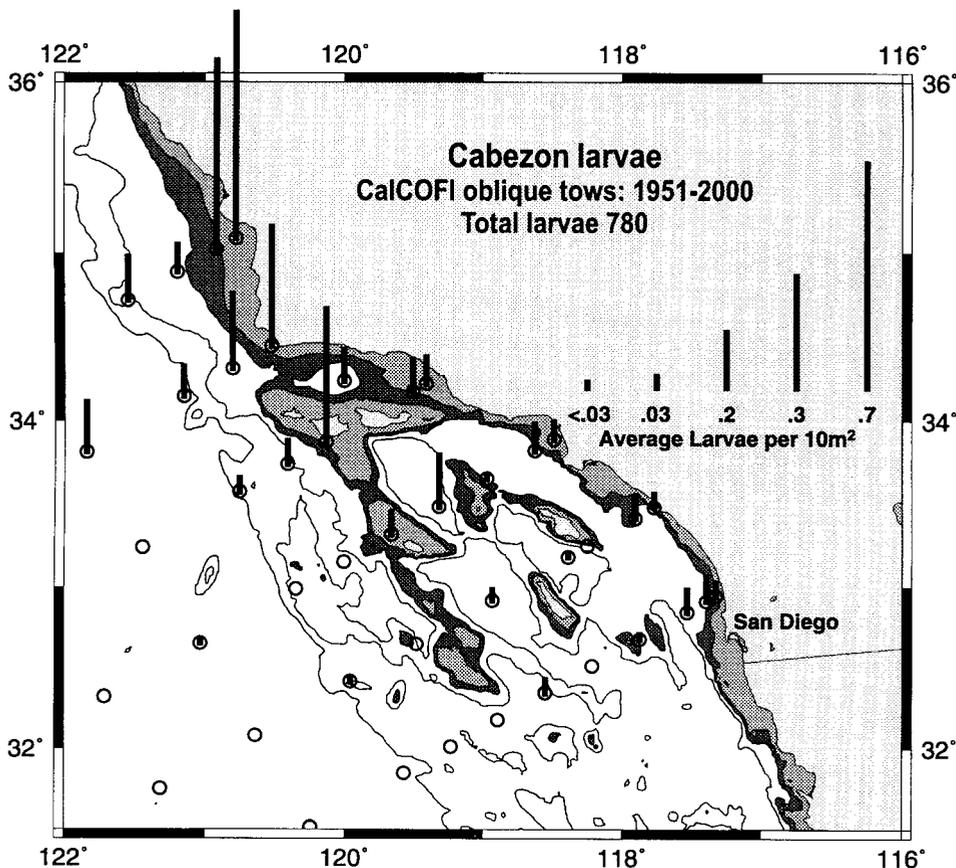


Figure 3. Average abundance of cabezon larvae in oblique tows at CalCOFI survey stations in the Southern California Bight region, 1951-2000.

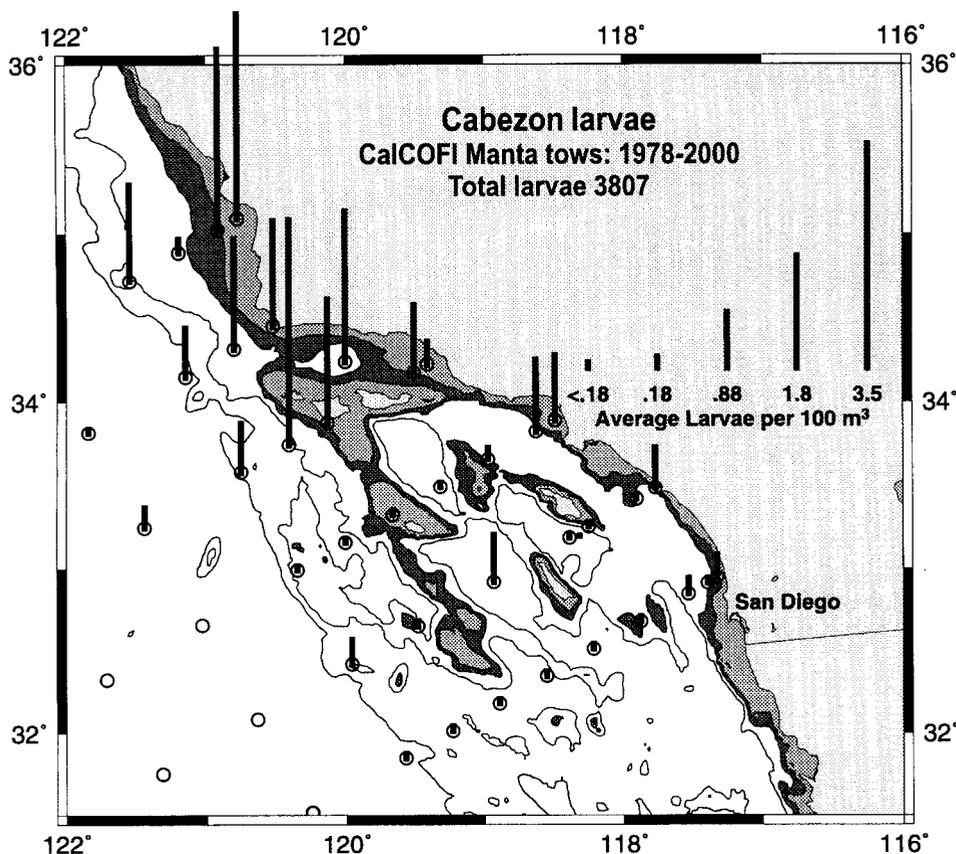


Figure 4. Average abundance of cabezon larvae in manta tows at CalCOFI survey stations in the Southern California Bight region, 1978–2000.

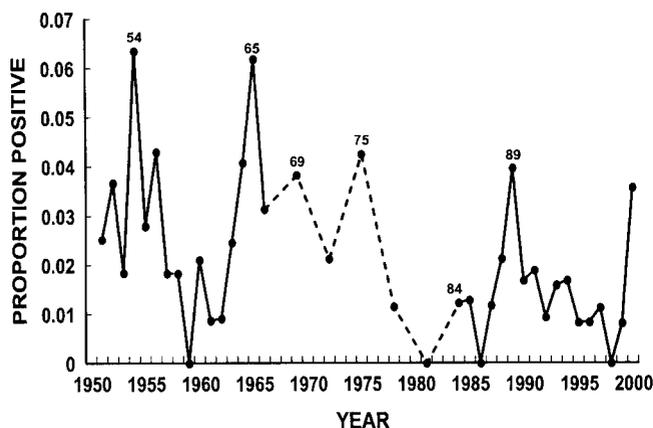


Figure 5. Occurrence (proportion of positive tows) of cabezon larvae in CalCOFI oblique tows in the Southern California Bight region, 1951–2000. Dashed line indicates the period of triennial surveys.

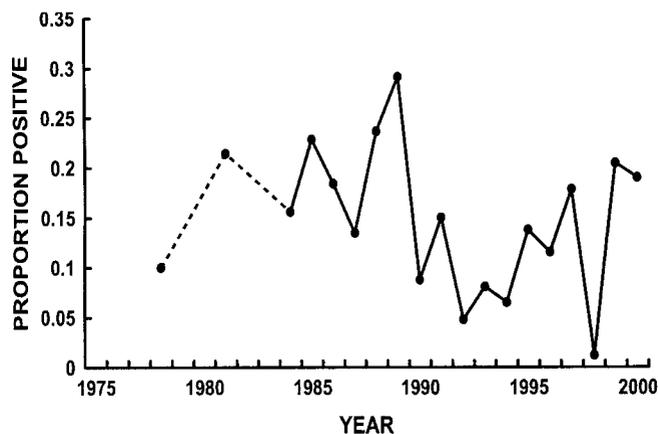


Figure 6. Occurrence (proportion of positive tows) of cabezon larvae in CalCOFI manta tows in the Southern California Bight region, 1978–2000. Dashed line indicates the period of triennial surveys.

with an approximately decadal cycle of high and low occurrence (fig. 5). Generally, occurrence peaked during cold episodes (1954–56, 1963–65, 1972–75, 1988–89, 1999), with the peaks tending to be progressively lower through the time series. Low occurrence was generally associated with years within warm episodes (e.g., 1957–59, 1978–81, 1997). The trends in larval occurrence match the trends in CPFV landings fairly closely. Average oc-

currences of cabezon larvae in manta tows for the years 1978–2000 are in general agreement with occurrences in oblique tows for that segment of the time series (fig. 6). Cabezon larvae are well represented in surface samples taken by Tenera at the intake bay for the power generating plant at Diablo Canyon (fig. 7). Occurrence declined during the years 1990–98 and is in general agreement with CalCOFI oblique and manta tow time

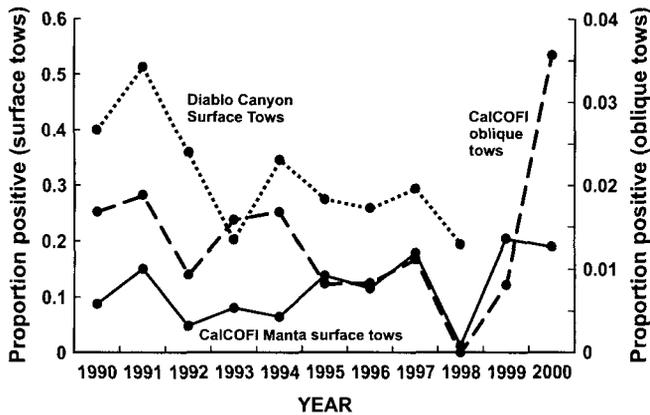


Figure 7. Occurrence (proportion of positive tows) of cabezon larvae in CalCOFI manta and oblique tows in the Southern California Bight region, 1990–2000, compared with occurrence of cabezon larvae in surface tows taken by Tena Environmental Services at the intake bay of the Diablo Canyon power station, 1990–1998.

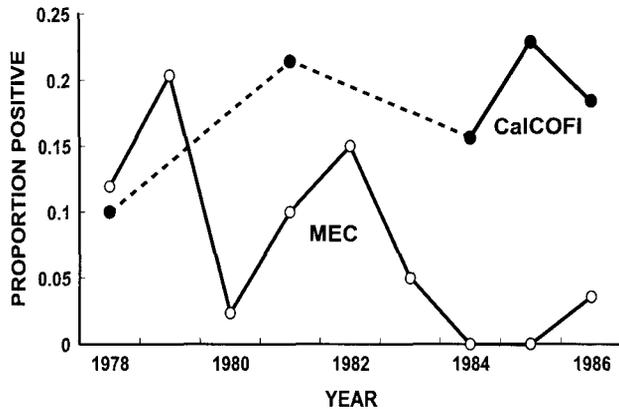


Figure 8. Occurrence (proportion of positive tows) of cabezon larvae in CalCOFI manta tows in the Southern California Bight region compared with occurrence of cabezon larvae in manta tows taken by MEC Analytical Systems off San Onofre, 1978–1986. Dashed line indicates the period of triennial surveys.

series during those years, although the minimum occurrence (~0.2 in 1993) was only slightly less than the proportion of positive tows in the year of highest average annual occurrence (1999) in CalCOFI manta tows. The trend for occurrence in CalCOFI oblique tows from the entire continental borderland closely matched the trend for surface tows at Diablo Canyon but was approximately tenfold lower (fig. 7). Within the SCB, occurrence of cabezon larvae in manta tows taken by MEC over the shelf at San Onofre shows an irregularly decreasing trend from 1978 to 1986 (fig. 8). Occurrence of cabezon larvae in CalCOFI manta tows over the entire continental borderland during that period was on the same scale; however, a year-to-year comparison of the two time series is precluded because of the missing years between CalCOFI triennial surveys. Cabezon larvae were too rare in LACM manta tows over the shelf in the central SCB to permit comparison with MEC and CalCOFI tows.

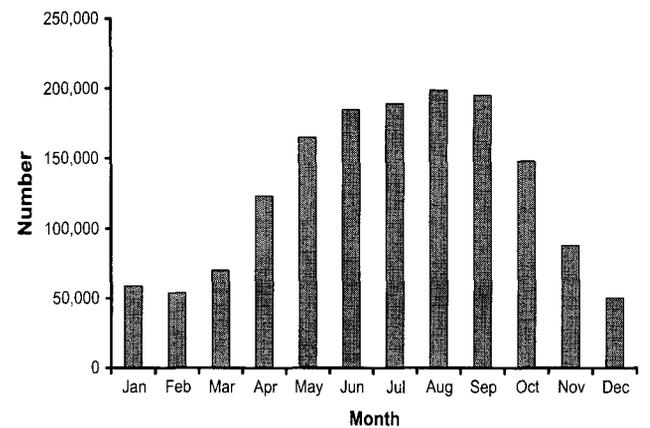
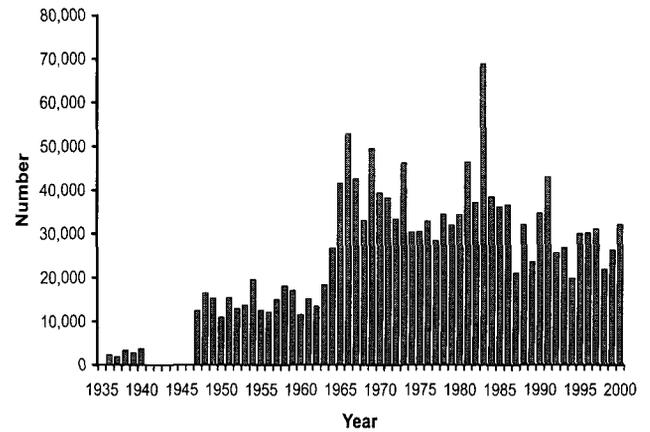


Figure 9. Total catch (numbers of fish) of sheephead from commercial passenger fishing vessels off California by year (above) and month (below); from database described in Hill and Schneider 1999.

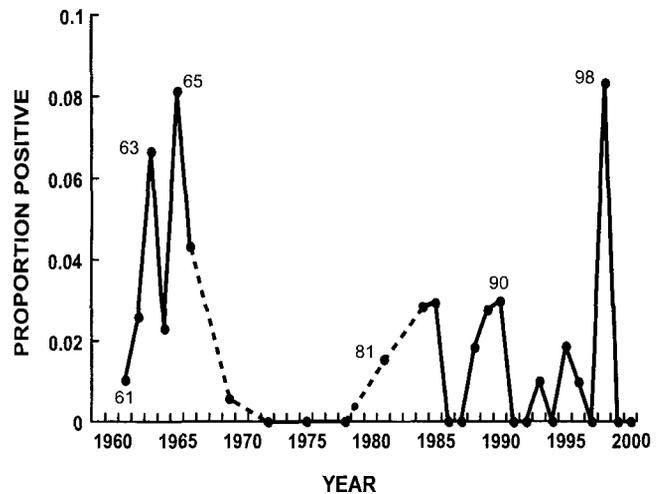


Figure 10. Occurrence (proportion of positive tows) of sheephead larvae in oblique tows at CalCOFI survey stations in the Southern California Bight region, 1961–2000. Dashed line indicates the period of triennial surveys.

Sheephead. Sheephead, like cabezon, are exploited by all nearshore fisheries. Commercial party vessel catch was stable from 1945 to the early 1960s, when it doubled (fig. 9). After 1966 it declined irregularly and more

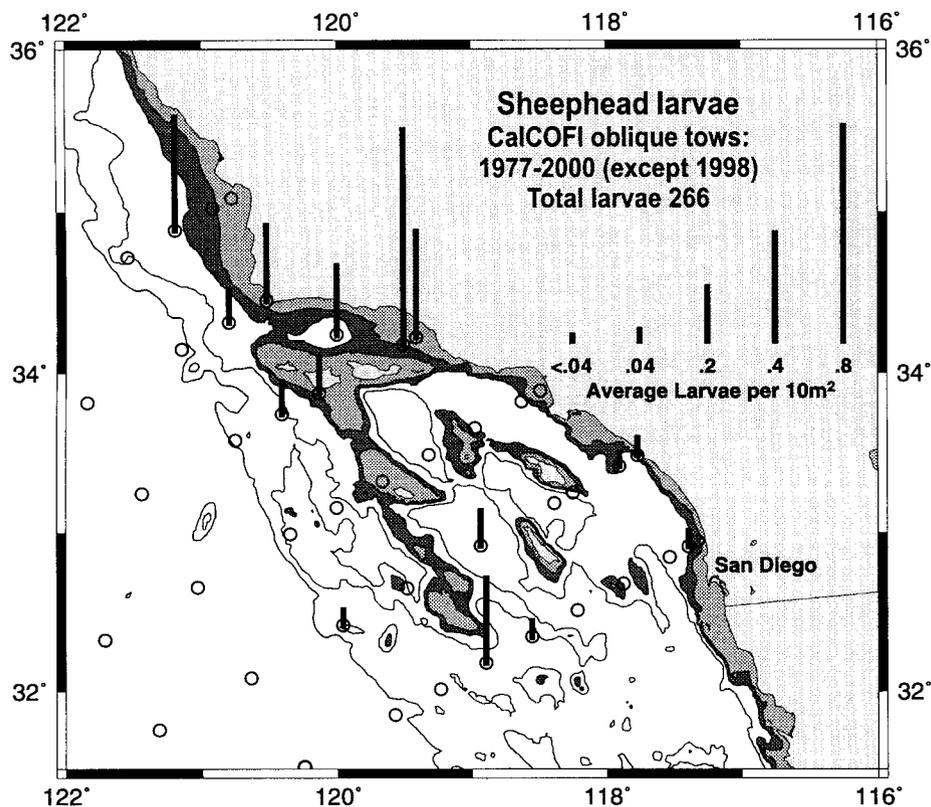


Figure 11. Average abundance of sheephead larvae in oblique tows at CalCOFI survey stations in the Southern California Bight region, 1977-2000 (1998 excluded).

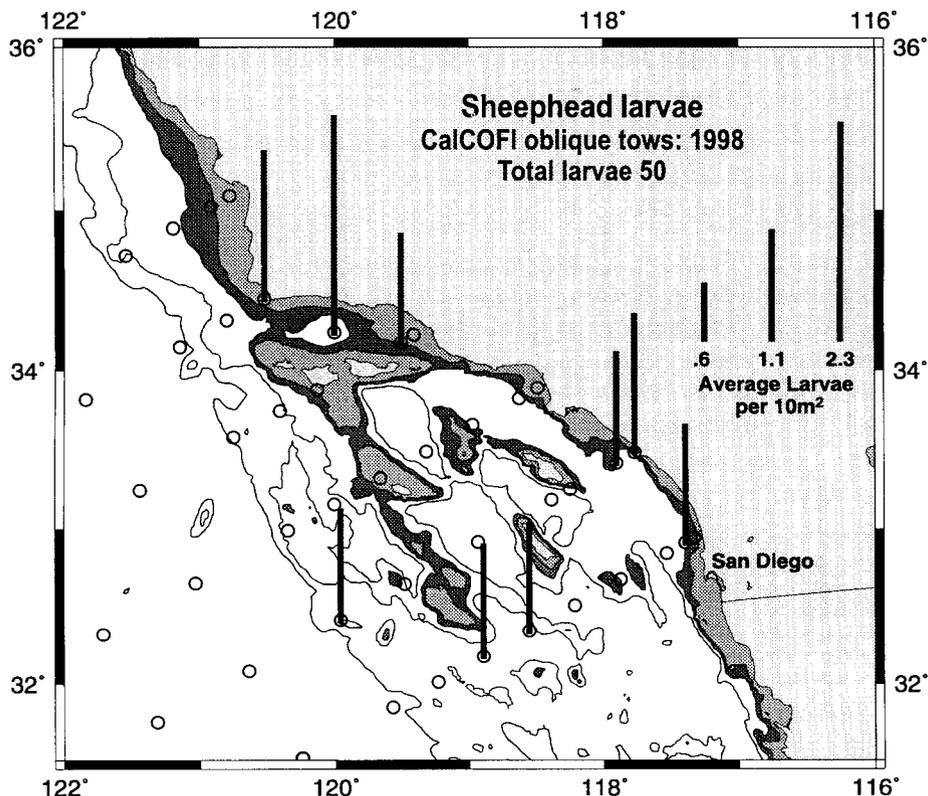


Figure 12. Average abundance of sheephead larvae in oblique tows at CalCOFI survey stations in the Southern California Bight region in 1998.

gradually than the cabezon CPFV catch. Like cabezon, the sheephead catch peaked during summer and early fall (fig. 9).

Identification of sheephead larvae in CalCOFI ichthyoplankton time series began in 1961. Peak occurrence of sheephead larvae in oblique tows in 1965 was followed by an abrupt decline in 1966 and 1969, and larvae were absent from the SCB during the prolonged cold episode of the early 1970s (fig. 10). The increase in 1981 corresponds to generally warm ocean conditions in the early to mid 1980s. The abrupt increase in larval occurrence in 1998 may represent an increase in transport of larvae northward from Baja California by the unusually strong Inshore Countercurrent generated during the 1997–98 El Niño. This is demonstrated by the distribution of sheephead larvae in the SCB during 1977–2000 (except 1998; fig. 11) compared to the distribution during 1998 (fig. 12). The general pattern is similar in both maps, with positive stations close to the mainland shore in the southern and northern sectors of the SCB and some positive stations offshore in the southern region of the SCB. Average abundance, however, was three times higher during the 1997–98 El Niño, and occurrence was consistently higher in the southern sector of the SCB compared with the 1977–2000 period. If we look at occurrence of sheephead larvae on individual CalCOFI cruises in the SCB during El Niño we see that larvae were absent until the summer cruise of 1998 and then peaked at >20% positive tows in the fall cruise of 1998 (fig. 13). Lynn and Bograd (in press) show that poleward transport measured on CalCOFI cruise 9711 was the largest ever documented in the entire CalCOFI time series (fig. 13). This and the much smaller transport event of summer 1998 may have contributed to the relatively high occurrence in the fall of 1998 (figs. 12 and 13).

A more direct response to the anomalously strong Inshore Countercurrent of 1997–98 was shown by the larvae of *Diogenes lanternfish* (*Diogenichthys laternatus*), an eastern tropical Pacific species, whose average occurrence in the SCB was six times higher in 1998 than in the highest previous year in the time series (fig. 14). The proportion of positive tows began to increase in the summer of 1997, reaching a peak of >30% positive tows in February 1998 (fig. 13). Approximately 23% of the total occurrences and 40% of the total larvae of this species in the entire CalCOFI time series from the present survey pattern were taken on this cruise. The sudden decrease in April was followed by another less spectacular increase in the fall cruise of 1998 and then a return to no occurrences in subsequent cruises. These transport events brought *D. laternatus* larvae to the SCB from waters off Baja California. The tropical affinity of *D. laternatus* is clearly shown in a map of larval abundance in the SCB (1998 excluded), where there are no

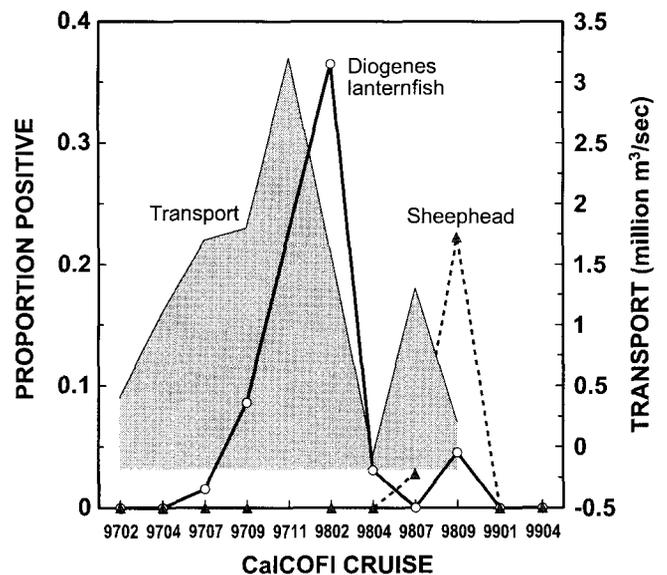


Figure 13. Occurrence (proportion of positive tows) of larvae of sheephead and *Diogenes lanternfish* (*Diogenichthys laternatus*) on CalCOFI cruises 9702 through 9904. Values for *D. laternatus* were calculated from all stations within the current CalCOFI survey. Shaded area indicates total transport (million m³/sec) of water by the Inshore Countercurrent from cruise 9702 to 9809 (data provided by Ronald Lynn, SWFSC, from Lynn and Bograd, in press).

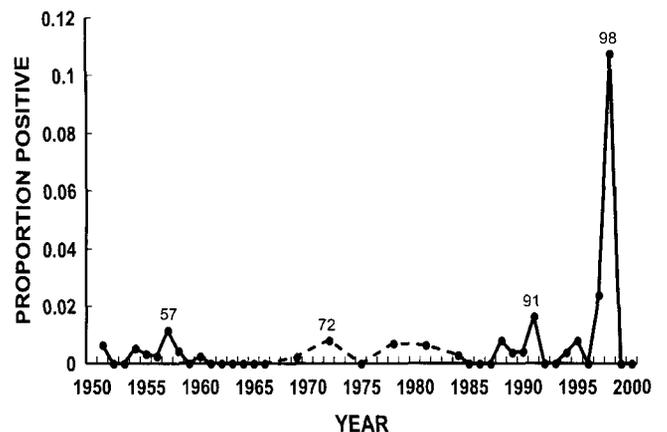


Figure 14. Occurrence (proportion of positive tows) of *Diogenichthys laternatus* larvae in oblique tows in CalCOFI surveys, 1951–2000. Dashed line indicates the period of triennial surveys.

occurrences north of CalCOFI line 87 (fig. 15) and average abundance is comparatively low over the continental borderland. In 1998 abundances were extremely high in coastal stations, where the Inshore Countercurrent was strongest and larvae were advected as far north as line 77, north of Point Conception (fig. 16).

Occurrence of sheephead larvae in oblique tows taken over the continental shelf in the SCB by LACM and MEC during 1978–86 follow similar trends, with the highest proportion of positive tows in 1979 and 1982 (fig. 17). Occurrence of sheephead larvae in CalCOFI oblique tows over the entire continental borderland during that period was on the same scale; however, years of

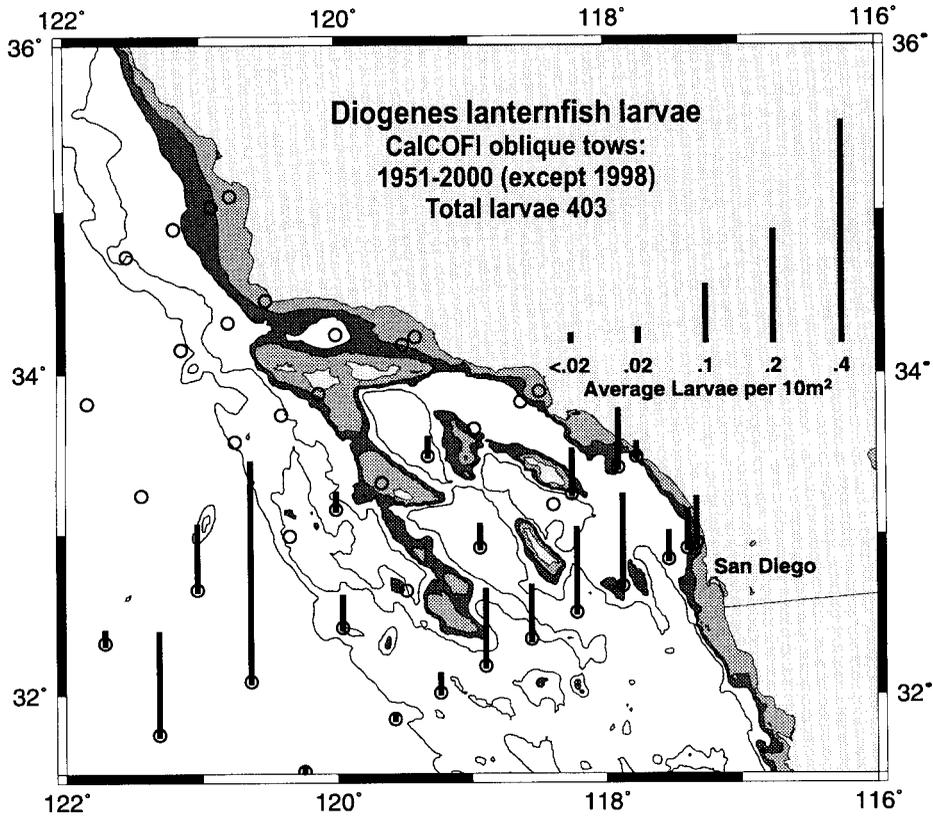


Figure 15. Average abundance of *Diogenichthys lanternatus* larvae in oblique tows at CalCOFI survey stations in the Southern California Bight region, 1951–2000 (1998 excluded).

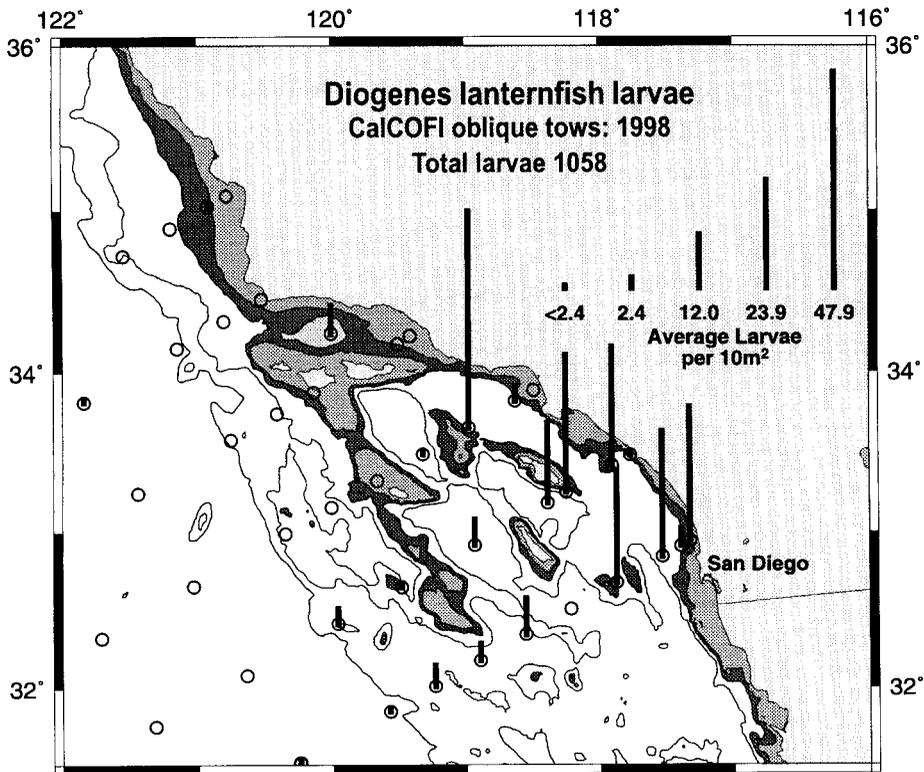


Figure 16. Average abundance of *Diogenichthys lanternatus* larvae in oblique tows at CalCOFI survey stations in the Southern California Bight region in 1998.

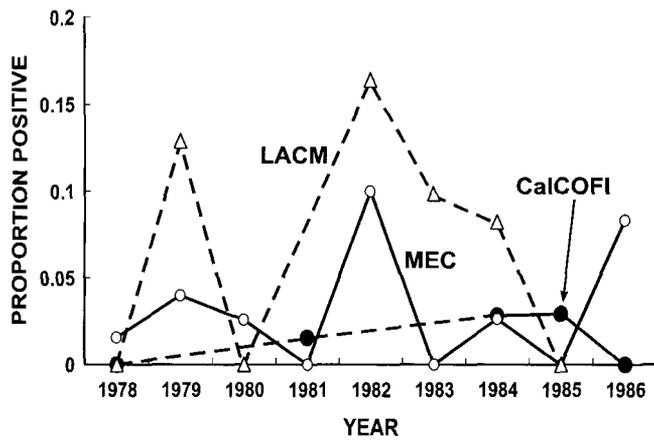


Figure 17. Occurrence (proportion of positive tows) of sheephead larvae in CalCOFI oblique tows in the Southern California Bight region compared with occurrence of sheephead larvae in oblique tows taken over the shelf by MEC Analytical Systems off San Onofre, 1978–1986, and by the Natural History Museum of Los Angeles County (LACM) in the central region of the Southern California Bight. Dashed segment of CalCOFI line indicates the period of triennial surveys

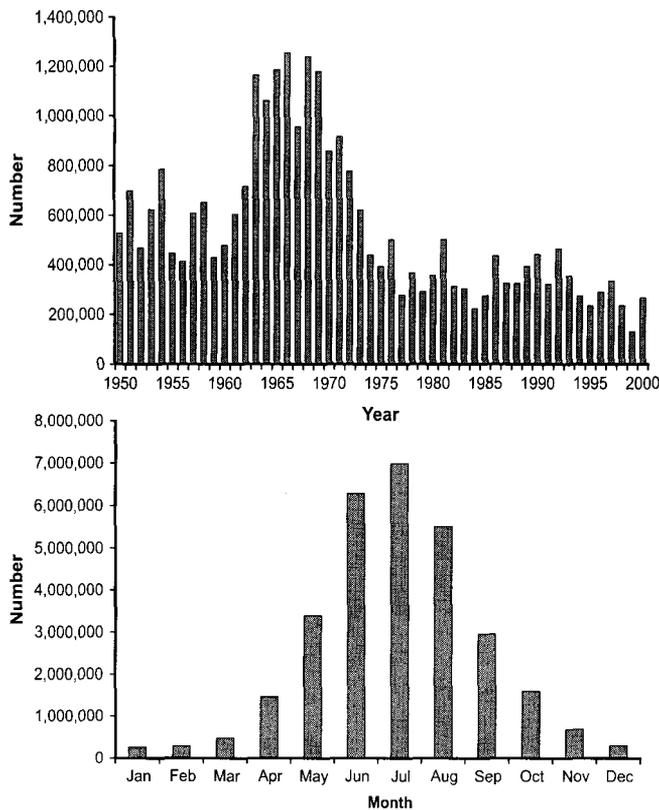


Figure 18. Total catch (numbers of fish) of kelp bass from commercial passenger fishing vessels off California by year (above) and month (below); from database described in Hill and Schneider 1999.

relatively high occurrence of sheephead larvae in the LACM and MEC time series (1979 and 1982) were not sampled by the triennial CalCOFI surveys.

Paralabrax spp. Kelp and barred sand bass are exploited primarily by private and commercial recreational fish-

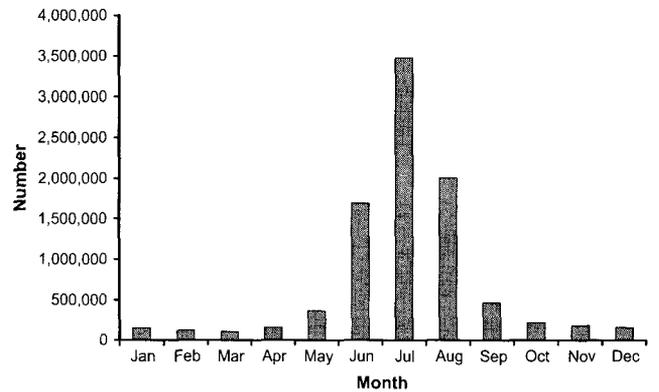
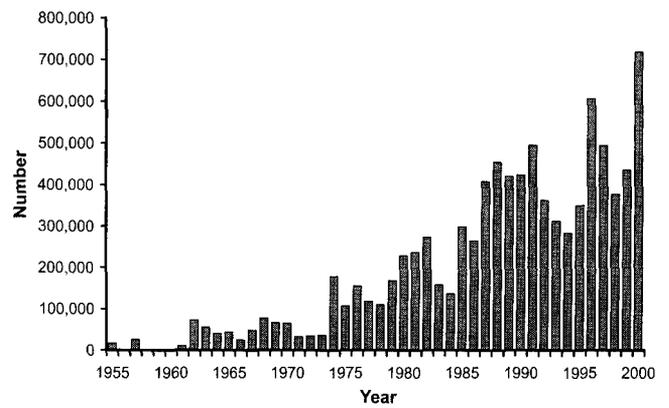


Figure 19. Total catch (numbers of fish) of barred sand bass from commercial passenger fishing vessels off California by year (above) and month (below); from database described in Hill and Schneider 1999.

eries. Trends for CPFV catches are strikingly different for these two species in the SCB (figs. 18 and 19). In the decade following WWII kelp bass catch was approximately three times greater than during the prewar period, and then doubled in the early 1960s, peaking at >1.2 million fish in 1966. Catch declined abruptly in the early 1970s to between 200,000 and 400,000 fish, with a trend of gradual decline to the present (fig. 18). Barred sand bass showed low catches until 1970, when the catch increased to a peak of >700,000 fish in 2000 (fig. 19). It appears that the two species have a compensatory catch history, with barred sand bass becoming targeted after the decline of kelp bass. Catch for both species peaks in July, but high catches of sand bass are restricted to summer months, whereas catches of kelp bass are relatively high from May to September (figs. 18 and 19).

The highest average abundance of *Paralabrax* spp. larvae in oblique tows typically was at the most nearshore station of survey lines within the SCB (fig. 20). On the three southernmost lines (87, 90, 93) abundance on the most nearshore station was 3–5 times greater than on the adjacent seaward station; however, abundance at the most nearshore station of line 83 was slightly lower than on the adjacent station. Except for stations associated

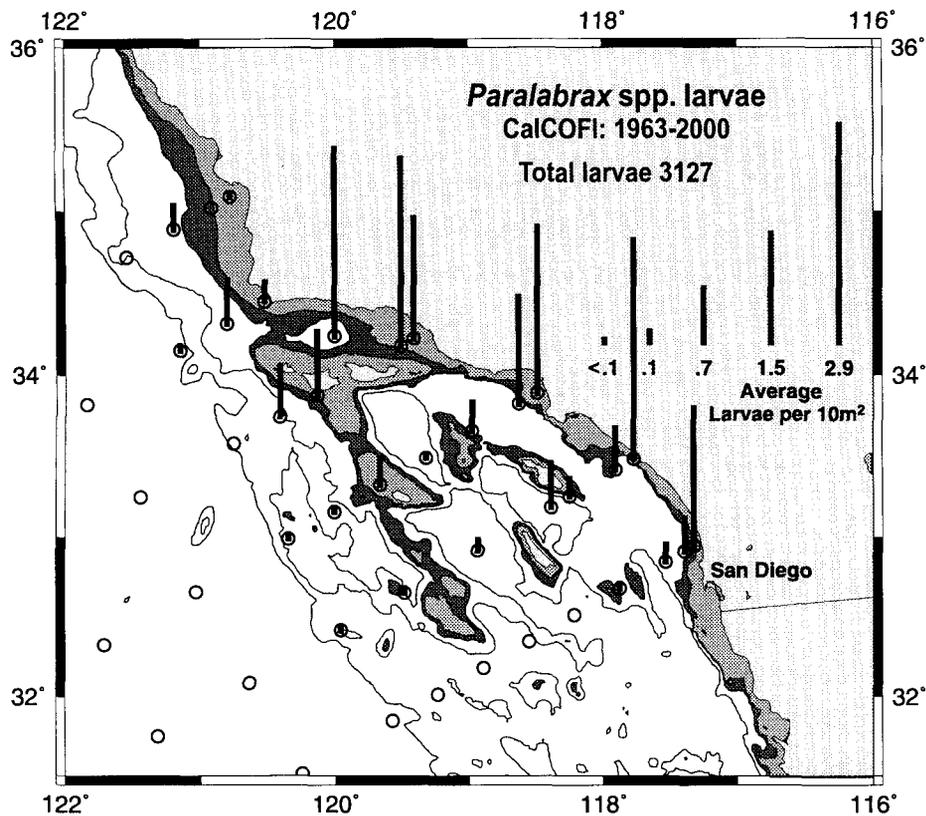


Figure 20. Average abundance of *Paralabrax* spp. larvae in oblique tows at CalCOFI survey stations in the Southern California Bight region, 1963–2000.

with offshore islands, abundance declined sharply seaward of the two most nearshore stations on each line. Average abundance was comparatively low at nearshore stations on the northernmost survey lines (77 and 80), reflecting the warm-water affinity of the genus (fig. 20).

Time series of occurrence of *Paralabrax* spp. larvae in oblique tows showed a series of decadal oscillations since 1963, with a pronounced decline from 1989 to 1995 and a generally decreasing trend for the available time series (fig. 21). The trend for incidence of *Paralabrax* spp. larvae is not directly comparable to the CPFV time series of the separate species since catches of kelp and sand bass follow opposite courses and appear to be compensatory; however, it is probable that the sand bass catch, like the kelp bass catch, will eventually decline with continued fishing pressure. Moreover, the trend for *Paralabrax* spp. larvae is similar to the CPFV trend for the numerically dominant kelp bass and may be a useful index of general population health for the genus. Occurrence of *Paralabrax* spp. larvae in CalCOFI oblique tows taken over the borderland and in MEC oblique tows taken over the continental shelf during 1978–86 followed similar trends (fig. 22). Occurrences in MEC tows showed

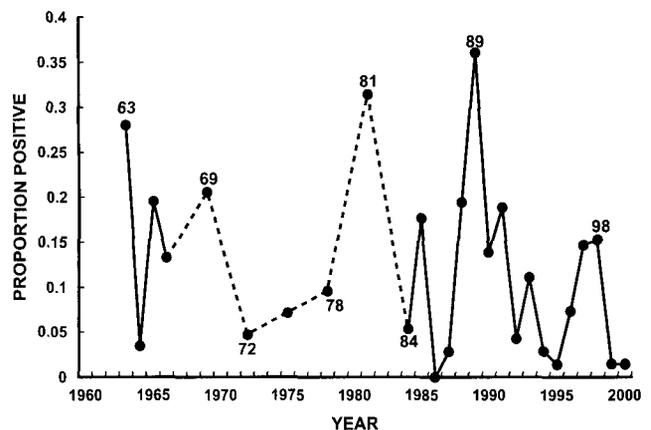


Figure 21. Occurrence (proportion of positive tows) of *Paralabrax* spp. larvae in CalCOFI oblique tows in the Southern California Bight region, 1963–2000. Dashed line indicates the period of triennial surveys.

a dome-shaped curve with highest values during 1982 and 1983. These years were not sampled by the triennial CalCOFI surveys, but the general agreement of values for years sampled by both surveys suggests that the MEC data could be used to estimate missing data in CalCOFI time series of *Paralabrax* larvae.

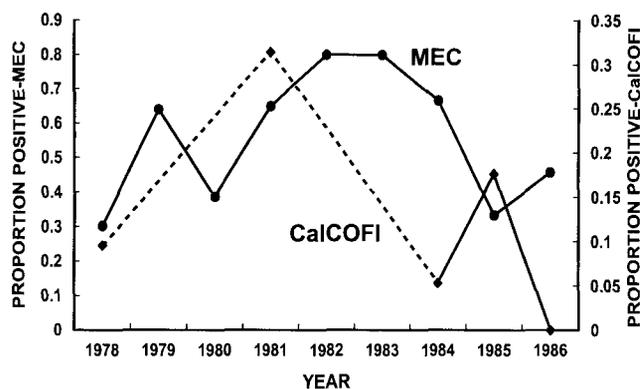


Figure 22. Occurrence (proportion of positive tows) of *Paralabrax* spp. larvae in CalCOFI oblique tows in the Southern California Bight region compared with their occurrence in oblique tows taken by MEC Analytical Systems off San Onofre, 1978–1986. Dashed segment of CalCOFI line indicates the period of triennial surveys.

DISCUSSION

Estimation of the size of marine fish populations by quantitative sampling of their larvae has become a useful tool in fishery management (Hunter and Lo 1993) despite the sources of potential imprecision inherent in this approach (Hauser and Sissenwine 1991). The daily egg production method provides a more direct means of estimating biomass and reduces the number of assumptions required in larval techniques (Lasker 1985; Hunter and Lo 1993); however, the method is relatively costly and is most useful for pelagic spawners. A modification of the technique, the daily fecundity reduction method, has proven useful for demersal spawners (Lo et al. 1992, 1993).

The value of indices of larval abundance or occurrence is dependent on the duration and sampling intensity of the time series from which they are derived. The CalCOFI surveys, designed for prolific, wide-ranging, pelagic spawners with dynamic life-history characteristics, have comparatively low sampling intensity in coastal regions. Nonetheless, larval indices of commonly occurring demersal species, derived from CalCOFI surveys, have proven to be effective means of tuning biomass models based on age-structured fisheries catch data. Formal population assessments of bocaccio and cowcod, incorporating CalCOFI larval abundance indices, have resulted in new harvest regulations by the Pacific Fisheries Management Council (PFMC) and the California Department of Fish and Game (CDFG) that are designed to conserve and rebuild these stocks (Ralston et al. 1996; Butler et al. 1999). Larval indices of rocky-shore species with less commonly occurring larvae may prove equally useful in developing management strategies. A formal population assessment of cabezon, planned for 2001, will rely on larval indices from CalCOFI time series for fishery-independent population trends, and a future assessment of sheephead is equally feasible. Catch curves for

cabezon generally match trends in CalCOFI larval indices, supporting use of the larval catch data as fishery-independent abundance indices.

How could CalCOFI larval indices be improved? Enhancing our ability to identify the larvae of nearshore rockfish species would be an important advance, particularly for species in the subgenus *Pteropodus*. This has proven difficult in the past because of the similarity of larval morphology and pigment patterns. The pigment pattern of *Pteropodus* larvae off central and southern California may be sufficiently distinct from patterns in larvae of co-occurring *Sebastes* species to permit identification to subgenus (Watson and Robertson, manuscript in prep.). Development of a time series of larval abundance of *Pteropodus* from reexamination of specimens in the archived CalCOFI ichthyoplankton collection would be useful but would require a large investment of effort and time. Direct identification of individual *Pteropodus* larvae by genetic markers is equally labor-intensive (Cynthia Taylor, pers. comm.). Ethanol-preserved samples from oblique tows taken on CalCOFI survey cruises over the past several years provide a means to genetically determine the extent that *Pteropodus* larvae occur in CalCOFI samples and the proportion of various species of the subgenus that may occur from year to year. This information could be used in combination with aggregate indices of *Pteropodus* larvae from CalCOFI archives to estimate historical changes in the abundances of individual *Pteropodus* species. Similarly, genetic identification of larvae of *Paralabrax* species from recent cruises could improve the CalCOFI time series of kelp and sand bass larvae.

An immediate improvement of the nearshore CalCOFI ichthyoplankton time series would be to reestablish plankton tows on CalCOFI survey cruises off central California north of line 77, the only line north of Point Conception on which standard plankton tows have been taken since the survey area was reduced in 1985 (see map of overall CalCOFI survey pattern on inside back cover of this volume). Prior to 1985, central California was surveyed, usually north to Point Arena (line 60), on approximately 60% of the CalCOFI cruises from 1951 to 1984. Since 1997, winter and spring CalCOFI surveys have occupied lines 60, 63, 67, and 70 off central California, taking continuous underway pump samples to measure sardine egg abundance. With one to two extra days of ship time, bongo and manta samples could be taken at the 18 historical stations on these lines out to, and including, station 60. Reestablishment of these net tow stations would permit comparison of current larval indices of rocky shore species with historical CalCOFI indices prior to 1985 and would provide information critical to the management of nearshore fishes. Ideally, net tow stations could be added

seaward of station 60 off central California if resources and research vessel time were to become available.

Would we improve our ability to assess nearshore fish populations by increasing the number of nearshore plankton tows on CalCOFI surveys within the SCB? Larval trends based on the present survey pattern have been adequate for formal PFMC biomass assessments of deep-water rockfish species (Ralston et al. 1996; Butler et al. 1999); however, species whose larvae remain close to shore may not be adequately sampled by the present CalCOFI survey pattern.

Average larval abundance of *Paralabrax* spp. was consistently low from the beginning of the time series until 1963, when nearshore net tow stations were added to the survey pattern, about a dozen on survey lines within the SCB. *Paralabrax* spp. larvae occur primarily in nearshore waters (fig. 20), and their low abundance prior to 1963, as well as the comparison with the MEC collections over the shelf, reflects inadequate sampling of this habitat. The larger CalCOFI catches since 1963 indicate that these larvae are dispersed seaward to some extent from the nearshore spawning sites, so that the seaward end of the larval distribution now falls within the CalCOFI sampling area.

Larval distributions of other important species may be even closer to shore than *Paralabrax* spp., and additional nearshore stations would improve larval indices for these species. Also, additional nearshore stations would improve indices for nearshore species whose larvae are relatively rare on CalCOFI surveys, and would reduce the chances of having zero occurrences for any given year.

Certainly we would need a higher station density to accomplish a biomass assessment of nearshore species based on egg or larval production. For example, during 1990–97, 88 to 124 (average of 112) samples per year were taken in the area of the CalCOFI survey pattern where cabezon larvae occur, during the months when they are present. Incidence of cabezon larvae was low, with the proportion of positive tows typically 0.01 to 0.02 for these years (fig. 5). The number of tows per year would have to be increased to 325–750 (average of 519) to obtain an acceptable coefficient of variation (e.g., CV of proportion positive = 0.4). Thus, a biomass estimate of cabezon based on larval production would require approximately five times as many samples as are presently taken on CalCOFI surveys (Nancy Lo, pers. comm.). Obtaining required age data of the larvae and data on fecundity and age structure of adults would add substantially to the cost of this method of assessment.

The shorter-term nearshore ichthyoplankton time series of LACM, MEC Analytical Systems, and Tenera Environmental Services provide data from shelf waters and are valuable adjuncts to CalCOFI time series. The most recent of these surveys, the sampling program con-

ducted by Tenera at Diablo Canyon, is just north of CalCOFI survey line 77 and proximate to CalCOFI station 77.49. Overall, Tenera took 8,657 tows (898 surface, 4,693 vertical, 3,066 oblique) in the vicinity of the Diablo Canyon power plant. The longest-running and most continuous part of Tenera's sampling program is the series of surface tows taken at weekly intervals at the intake cove at Diablo Canyon.² Fish larvae from these samples have been identified for the years 1990–98, but unsorted samples for 1999 and 2000 could be processed if funding were available. Retrieval of these data from existing samples would be highly cost-effective, as would support to continue this sampling program in the future.

The intensive sampling programs conducted over the SCB shelf by MEC and LACM are valuable complements to CalCOFI survey data. MEC took 3,023 tows (985 surface, 1,044 oblique, 994 epibenthic) at quarterly to weekly intervals on two transects in the San Onofre area from 1978 to 1986. LACM took a total of 2,518 tows (485 surface, 1,648 oblique, 385 epibenthic) between 1978 and 1985, but not all sites were sampled in all years. During 1978–79, the first year of the program, 10 shelf transects encompassing the entire SCB were sampled with a full array of samplers. In the following year, 1979–80, 20 shelf transects spanning the SCB were sampled with oblique tows. These were augmented by surface and epibenthic samples on three transects in the central SCB. During 1982–85 sampling was restricted to oblique tows at 4 shelf transects in the central SCB (off Ormond Beach, Playa Del Rey, Seal Beach, and San Onofre). Thus, the LACM series provides data on a wider selection of sites in the SCB than the MEC time series but is less site-consistent. LACM's synoptic bight-wide surveys of 1978–80 are the only such surveys ever taken over the SCB shelf.

Data from these nearshore surveys can be used to fill in missing data from years when CalCOFI surveys were run on a triennial basis. Another important feature of these additional surveys was their comprehensive sampling of the entire water column with surface, oblique, and epibenthic nets. Information on vertical distribution of larval stages resulting from this approach is important in interpreting life-history strategies and in quantitative evaluation of each type of tow. For example, some nearshore species—e.g., white croaker (*Genyonemus lineatus*), queenfish (*Seriphus politus*), and other croakers—produce planktonic eggs, but a large fraction of the larvae settles to the epibenthos early in the larval period (Schlotterbeck and Connally 1982; Barnett et al. 1984; Brewer and Kleppel 1986; Jahn and Lavenberg 1986). Undersampling the larvae of these species with oblique tows is further complicated by diel behavior that results

²See footnote 1 on page 113.

in higher concentrations of larvae in the epibenthos during the day than at night (Jahn and Lavenberg 1986). Larvae of another croaker species, white seabass (*Atractoscion nobilis*), settle to the epibenthos soon after hatching and recruit to submerged drift algae in the subtidal zone (Allen and Franklin 1992). Many nearshore species (e.g., some gobies, cottids) that brood eggs in nests produce larvae that settle to the epibenthos soon after hatching (Barnett et al. 1984; Jahn and Lavenberg 1986) and would be poorly sampled by oblique tows even if the tows reached the epibenthic layer. Marliave (1986) showed that larvae of some cottid, stichaeid, pholid, and gobiesocid species remain within several meters of the rocky shoreline, even at newly hatched stages. They appear to school early in the preflexion stage and have the capacity to maintain their position near rocky substrate features. Other species, including nearshore rockfish species, may be able to maintain proximity to shore, but this has not been demonstrated. Species whose larvae are primarily neustonic (e.g., cabezon, lingcod, greenlings) are undersampled by oblique net tows because the surface layer is filtered only briefly at the beginning and end of each tow. The manta net time series, begun on CalCOFI survey cruises in 1978, permits better sampling of these species.

An important facet of CalCOFI survey data is the information that they can provide on the relation between larval production and ocean climate. The potential for advection of larvae northward into the SCB from Baja California by the Inshore Countercurrent during El Niño episodes has been discussed in this paper. Such transport events could be important sources of larvae and pelagic juveniles of species such as sheephead, with large populations off Baja California. Cowen (1985) found anomalously large numbers of newly settled sheephead in 1983 at the northern Channel Islands within the SCB and noted similar settlement success at other localities as far north as Monterey Bay, California. He suggested that this could have resulted from advection of sheephead larvae into the SCB from population centers off Baja California by the strong Inshore Countercurrent that developed during the 1982–83 El Niño. Information presented in this paper on the distribution and abundance of larval sheephead and *Diogenes* lanternfish during the 1998 El Niño supports Cowen's (1985) hypothesis and suggests that a strong 1998 year-class could have resulted from these events.

Another potential use of the CalCOFI ichthyoplankton time series is to separate the effects of fishery removals from those of ocean climate by comparing larval production of species that share similar habitats and life-history characteristics but differ in degree of exploitation. One such pair is the heavily exploited bocaccio and the relatively unexploited shortbelly rockfish

(Moser, Charter, Watson et al. 2000). Time series of these two species show that both had a general trend of decreasing abundance, with sharp declines in both species during the 1957–59 El Niño and a sharp decline during the transition from the cool to the warm ocean regime in 1976–77. The fact that both species declined during the transition from cool to warm regime even though one was exploited and one was not suggests an environmental effect on larval production. The contrasting trends in larval abundance for these species during the warm regime suggest that other factors are affecting larval production as well. The larval trend for bocaccio followed the steadily declining trend for adult biomass (MacCall et al. 1999) and suggests that fishery removals were the principal cause. In contrast, the recovery of shortbelly larval production during the warm regime suggests that some other factor, possibly one or more good year-classes, resulted in a sustained increase in larval abundance that peaked in 1991 (Moser, Charter, Watson et al. 2000).

The CalCOFI ichthyoplankton time series has proven to be an important resource in the monitoring and management of coastal pelagic fish stocks and promises to be equally useful for nearshore species that have experienced increasing pressure from fisheries and environmental perturbation. In addition to providing indices for individual species, the CalCOFI time series could be used to construct long-term indices of community structure in the nearshore environment. For example, one could calculate the ratio of abundances of the larvae of fished rocky-shore species to the larvae of unfished, or lightly fished, species (e.g., those listed under "other species" in table 2). Essentially this would be a dimensionless index of ecosystem "health," with the standard for the ratio being data collected 50 years ago. One could then monitor trends in the community (i.e., the ratio over time) to track the extent to which the fished species become a smaller fraction of the community. This index could include nearshore soft-substrate species (table 3), or a separate index could be constructed for them. The CPFV data are beginning to indicate increasing fishing effort on shallow-water soft-substrate species because of fishing restrictions on rocky-substrate fauna. Pre-crisis assessment and monitoring of these stocks by means of fishery-independent abundance indices would be prudent.

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TABLE 3
Larvae of Soft-Substrate Fish Taxa* in CalCOFI
Samples in the Southern California Bight Region,
by Overall Abundance

Common name	Scientific name	Rank	Time series
Fisheries species			
White croaker	<i>Genyonemus lineatus</i>	26	1981–2000
Pacific sanddab	<i>Citharichthys sordidus</i>	28	1954–1960; 1984–2000
English sole	<i>Parophrys vetulus</i>	44	1952–2000
California halibut	<i>Paralichthys californicus</i>	50	1951–2000
Dover sole	<i>Microstomus pacificus</i>	71	1951–2000
Rex sole	<i>Glyptocephalus zachirus</i>	104	1951–2000
Longspine thornyhead	<i>Sebastolobus altivelis</i>	155	1985–2000
Shortspine thornyhead	<i>Sebastolobus alascanus</i>	194	1985–2000
Other species			
Speckled sanddab	<i>Citharichthys stigmaeus</i>	16	1954–2000
Pacific argentine	<i>Argentina sialis</i>	37	1951–2000
Slender sole	<i>Lyopsetta exilis</i>	45	1951–2000
Hornyhead turbot	<i>Pleuronichthys verticalis</i>	56	1951–2000
Pacific butterfish	<i>Peprilus simillimus</i>	59	1951–2000
Queenfish	<i>Seriplus politus</i>	67	1981–2000
California tonguefish	<i>Symphurus atricaudus</i>	76	1951–2000
Basketweave cusk-eel	<i>Ophidion scrippsae</i>	88	1951–2000
Bigmouth sole	<i>Hippoglossina stomata</i>	93	1951–2000
Bay goby	<i>Lepidogobius lepidus</i>	100	1985–2000
Yellowchin sculpin	<i>Icelinus quadriseriatus</i>	101	1985–2000
Spotted cusk-eel	<i>Chilara taylori</i>	106	1951–2000
C-O turbot	<i>Pleuronichthys coenosus</i>	108	1951–2000
Spotted turbot	<i>Pleuronichthys ritteri</i>	122	1951–2000
California lizardfish	<i>Synodus lucioceps</i>	124	1951–2000
Longspine combfish	<i>Zanilepis latipinnis</i>	125	1985–2000
Curlfin turbot	<i>Pleuronichthys decurrens</i>	132	1951–2000
Longfin sanddab	<i>Citharichthys xanthostigma</i>	134	1954–1960; 1985–2000
Fantail sole	<i>Xystreurys liolepis</i>	137	1951–2000
Sand sole	<i>Psettichthys melanostictus</i>	153	1951–2000
Diamond turbot	<i>Hypsopsetta guttulata</i>	157	1951–2000
Shortspine combfish	<i>Zanilepis frenata</i>	163	1985–2000
Roughback sculpin	<i>Chitonotus pugetensis</i>	176	1985–2000
Rock sole	<i>Lepidopsetta bilineata</i>	179	1951–2000
Blacktip poacher	<i>Xeneretmus latifrons</i>	183	1985–2000
Pygmy poacher	<i>Odontopyxix trispinosus</i>	188	1985–2000
Bluebarred prickleback	<i>Plectobrauchus evides</i>	191	1985–2000

*Limited to taxa with 100 or more total larvae (larvae per 10 m², summed over the time series).

the net tows and associated data, as well as for the excellent condition of the fish eggs and larvae captured in the nets. Lucy Dunn has been the mainstay of our group of plankton sorters over the past three decades. Susan Manion was responsible for data entry during this project. We are especially indebted to Susan Jacobson for her contributions in data management and programming. We thank Henry Orr for his work on the graphics and Richard Cosgrove for his help with bathymetric data. We thank Nancy Lo for helpful discussions on sampling and for her estimates of sampling requirements. We are indebted to John Hunter, Chief of the Fisheries Resources Division, for his support, encouragement, and helpful suggestions. Karen Green, MEC Analytical Systems, provided advice on the MEC ichthyoplankton database, and Steven Schroeter, Marine Science Institute,

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LONG-TERM TRENDS OF INTERANNUAL VARIABILITY IN THE CALIFORNIA CURRENT SYSTEM

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ABSTRACT

Several series of physical and biological parameters from the California Current region were analyzed for coherent long-term (>20 years) trends of change. Three different scales of change, related to the availability of data and different degrees of precision, were obtained: one for the period of most extensive and intensive CalCOFI sampling, roughly 1951–98; the second for the full century; and the third for the last 2,000 years.

Only one regime shift—that of the mid-1970s—was found in the shorter series. The shift consists of a long-term trend reversal, including both physical and biological data; no sudden step was found. The century-long series reveals two other shifts, both consisting of long-term trend reversals, the first in the early 1910s and the second during the early 1940s. Three other less certain shifts seem to have occurred about 1860, 1880, and 1900. If these indications are true, the ~60-year cycle of sardine abundance may have been much more variable than previously believed.

Sardine abundance appears to be enhanced during warm periods and diminished during cool ones; outbursts are very dynamic, lasting only a few decades. Regimes should be related to the change itself (either warming or cooling), rather than to warm or cool periods. Thus, the main factor for change might not be temperature, but possibly large-scale ocean current changes and associated alterations in wind systems. We found monitoring biological indices to be the most feasible tool for nowcasting regime shifts. There is not yet enough information for long-term forecasting.

INTRODUCTION

At their first meeting, held in 1998, the Living Marine Resources Panel of the Global Ocean Observing System (LMR-GOOS) decided to conduct a series of retrospective analyses at well-known ocean areas in order to examine whether ocean changes could have been forecasted on the basis of present knowledge. The authors conducted such an experiment for the California Current system (CCS), one of the best known regions, particu-

larly following the intensive, extensive, and persistent work conducted by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) program.

The analysis was rather limited and particularly focused to find readily available environmental and biological variables that could prove practical for monitoring and eventually forecasting change. We selected some of the most commonly accessible variables, such as sea-surface temperature, sea-level height, and upwelling as indices of physical change; we used macrozooplankton volumes, larval fish species abundance, and sardine and anchovy relative abundance as biological indices. Although these variables are not exhaustive reflections of change, they are somehow related to it and easily obtained.

In this paper we discuss trends of such variables at longer than 20-year periods; this scale corresponds to the very low frequency described by Ware (1995). A number of authors use the term *regimes* to denote multidecadal periods separated by shifts. The duration of these regimes and the timing of their onset and end have been examined by several authors (fig. 1). Hubbs (1948) described both annual and long-term persistent changes based on the presence of southern- and northern-affinity fauna; in particular, he described the warm period during the 1860s.

Lluch-Belda et al. (1989), looking at sardine and anchovy population abundance, pointed out high sardine abundance during the 1930s–40s and low abundance during the 1960s–70s. Michaelsen (1989) extracted an El Niño–Southern Oscillation (ENSO) index from tree rings of northern Mexico and the southwestern United States and found that both the amplitude and frequency of the signal were modulated over an 80–100-year time scale.

Baumgartner et al. (1992) analyzed sardine deposition rates at varved sediments and found a predominant signal of about 60 years in both sardines and anchovies and about 100 years for anchovies, but not for sardines.

A different approach to the problem was taken by Ebbesmeyer et al. (1991), who examined the 1976–77 climate shift (Kerr 1992) and demonstrated how a wide array of both biological and environmental variables changed during the period.

Francis and Hare (1994) described regime shifts dur-

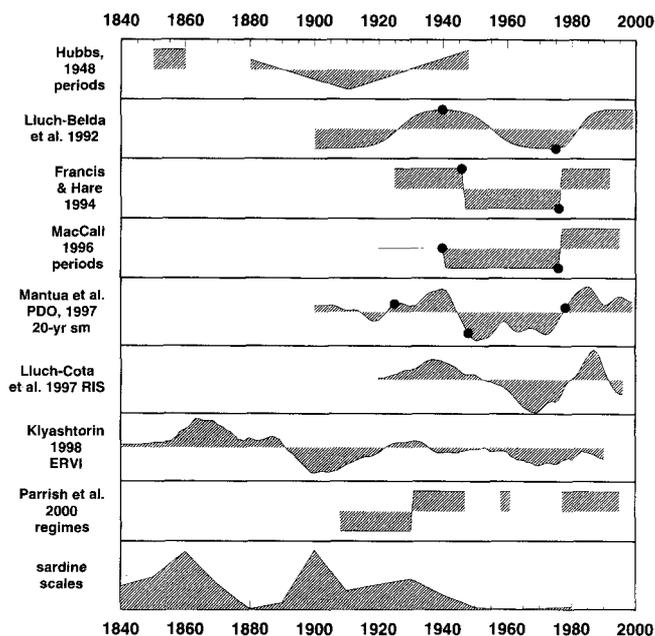


Figure 1. Schematic representation of warm and cool periods and timing of regime shifts, after several authors.

ing the late 1940s and the late 1970s in the northeast Pacific, based on several environmental variables and two biological indices (zooplankton and salmon production). Ware (1995) analyzed changes in the marine climate of the NE Pacific, particularly British Columbia, and found five principal periodic signals: the QBO (quasi-biennial oscillation, ~2–3 years); two ENSO-related (~5–6 and ~11–14 years); the BDO (bidecadal oscillation, ~20 years); and the VLF (very low frequency, ~50–90 years).

Polovina et al. (1995) found that from 1976 to 1988, a period of intensified Aleutian Low, there was a deepening of the mixed layer in the eastern subtropical Pacific and shoaling in the Gulf of Alaska, as compared to the 1960–76 period. Hsieh et al. (1995) found intensified winter downwelling along Alaska and British Columbia and intensified winter upwelling off Baja California since 1940.

MacCall (1996) reviewed low-frequency variability of fishes in the CCS and referred to biological variability in 50–70-year scales; he further noted that the conditions after 1976 were similar to those of 1850–70. He described the regime shifts of 1940 and 1976 and discussed the evidence of a brief cold period around 1890.

Brodeur et al. (1996) and more recently Ingraham et al. (1998) report on a surface drift simulation model (OS-CURS) which showed that winter trajectories beginning at Ocean Station P drifted more toward the CCS before 1976 and more into the Alaska Current after 1976.

Mantua et al. (1997) calculated the Pacific decadal oscillation index (PDO) and found it to be predominantly positive during 1925–46, negative in 1947–76, and again

positive since 1977. They further proposed 1925, 1947, and 1977 as dates of climate shift.

Lluch-Cota et al. (1997) analyzed environmental variability together with sardine and anchovy population abundance in a global perspective and concluded that climate regime trends and periods lasted for several decades (more than two, less than four) in the twentieth century; they also found that from 1870 to 1915 the periods were shorter. Sardines were abundant from 1925 to 1950 (peaking during the mid-1930s), and anchovies from the early 1950s to the late 1970s (peaking around the late 1960s); sardine abundance increased again from the late 1970s and in most of the 1980s, perhaps declining in the early 1990s.

Looking at mesoscale disturbances in the American southwest, Swetnam and Betancourt (1998) showed that the first part of the century (1905–30) had wet winters, followed by a dry period from 1942 to 1964; after 1976, winters have been wet and warm, with erratic summers.

One of the few papers that deal with long-term trends of change in this temporal scale is that of Klyashtorin (1998), who reports the similarity of trends between the abundance of several fish stocks and large-scale environmental variables, mostly related to the atmospheric circulation index, the length of day index, and the earth rotation velocity index (ERVI). This last index shows some interesting similarities to the rest, although the peaks and troughs are somewhat dephased.

Parrish et al. (2000) reviewed previous information together with an analysis of wind data and arrived at a number of relevant conclusions, including that surface water entering the CCS was of more subtropical origin after 1976. Parrish et al. considered the best example of decadal climatic change to be the 1976 shift. After 1976, the surface of the central North Pacific cooled by 1°C or more, while the North American coast and Gulf of Alaska warmed by a similar amount. Further, there was ~20 m shoaling of the mixed layer depth in the Subarctic Gyre after 1976, and a similar deepening in the Subtropical Gyre. Dynamic heights and SST increased in the Gulf of Alaska after 1976; transport into it increased, while transport decreased into the California Current.

Parrish et al. (2000) further noted that the principal source of the biological bonanza in the CCS during the late 1970s lay in processes associated with the shift from one climate state to the other, not in the new state itself. With regard to multidecadal periods, they found an extensive cold period from 1908 to 1930 and warm intervals during 1931–47, 1958–61, and 1977–95.

Minobe (2000) examined the interaction between the bidecadal and pentadecadal variation in the North Pacific and suggested that major regime shifts are caused by the phasing of both cycles, as occurred during the 1920s, 1940s, and 1970s shifts, while minor regime shifts (such

as that of 1988–89) could be caused by the bidecadal variation alone. Minobe and Mantua (1999) found that interannual variance in the strength of the Aleutian Low was large during the mid-1920s to the mid-1940s and during the 1980s, but low from 1899 to the mid-1920s and from the mid-1940s to the mid-1970s. Hare and Mantua (2000) studied the proposed 1989 regime shift by analyzing a large number of biological and physical series, and concluded that although the biological series offer strong support for the case, the physical series are less convincing.

The published information discussed above leads to a number of possible conclusions:

1. There have been multidecadal, irregular, alternating climatic periods in the 50–100-year range.
2. The most documented regime shift occurred around 1976.
3. Other likely shifts have occurred in the 1940s and between 1910 and 1927, with lessening certainty.
4. The best-documented prolonged period is the cool one extending from about 1940 to the late 1970s; the warm stretch after it is possibly coming to an end (Ware 1995; MacCall 1996; Lluch-Cota et al. 1997) or has already ended (Hare and Mantua 2000).
5. An additional cool period seems to have occurred about the 1910s; another might have been present about 1890.
6. Other earlier warm periods have likely happened during the 1930s–40s and about 1850–60. If there was a cold period about 1890, then a short warming might have been present at about 1890–1900.
7. During warming periods, the mixed layer at the eastern subtropical Pacific deepens while it shoals at the Gulf of Alaska. Also, the flow of the Alaska Current intensifies while that of the CCS relaxes. Links to atmospheric changes are suggested both by the relative interannual variability in the strength of the Aleutian Low and by the parallel alternation of dry and wet winters in the southwestern United States.

In this paper, we examine several biological and environmental data series in the framework of these long-term changes.

Three temporal windows result from data availability: (1) 1950–present, roughly half a century: for upwelling and most biological indices (zooplankton volumes, larval fish species abundance, and sardine and anchovy relative abundance); (2) century-long: mostly for sea-surface temperature, sea-level height, and sardine fishery data; (3) millennial proxies: basically global temperature, sea-surface temperature, and sardine and anchovy scale numbers in varved sediments as indices of their relative abundance.

DATA AND METHODOLOGY

We extracted monthly average SST series from the COADS database (Mendelssohn and Roy 1996) for the 76 $2^\circ \times 2^\circ$ quadrants shown in figure 2, assuming that it covered most of the CCS. The annual cycle of each quadrant was estimated as the average SST for each month for all the existing data between 1900 and 1990. Anomalies were then calculated as the yearly average of the monthly departures from the mean. The global index (AST) was obtained by annually averaging the individual yearly anomalies at all 76 quadrants. Principal component analysis (see Storch and Zwiers 1999) was used to estimate the first principal component of the averaged yearly anomalies for each quadrant (from now on, PST).

Yearly averaged SST anomalies were also estimated from data at coastal stations and were obtained from the PACLIM database (updated after Cayan et al. 1991), including Point Hueneme, Crescent City, Pacific Grove, Los Angeles, San Francisco, and San Diego (CST = coastal SST anomalies). Yearly anomalies were estimated as the averaged departures from the monthly means of the full series. Average yearly air temperature anomalies for the conterminous United States were obtained by digitizing figure 2 in Karl et al. 1995. Global air surface temperature anomalies and global SST anomalies were obtained from the Web site of the British Meteorological Office (<http://www.metu.gov.uk/>).

Monthly sea-level height was obtained from the University of Hawaii Sea Level Center Web site (<http://uhslc.seest.hawaii.edu>) for San Francisco and San Diego. We

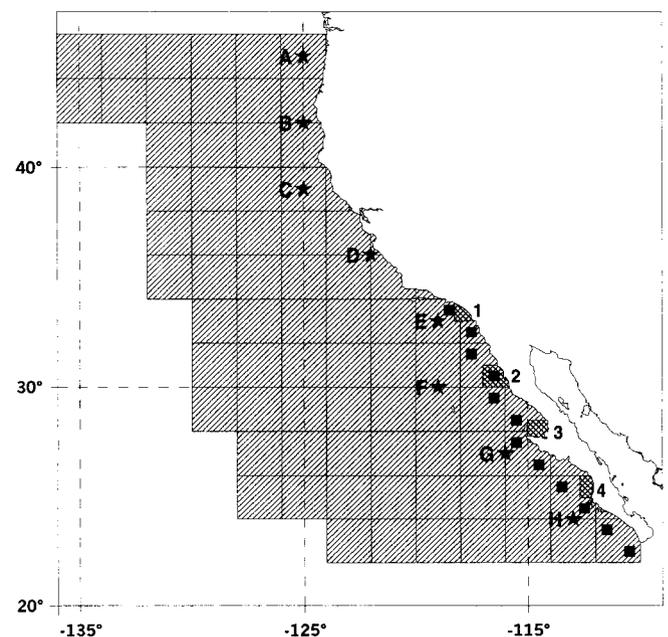


Figure 2. General map of the U.S. West Coast and Baja California area, showing the location of the 76 COADS quadrants (hatched) and their latitudinal transects; the four coastal areas for biological indices (crosshatched); SST anomalies sites (■) and upwelling indices (★), reconstructed for this paper.

detrended and standardized both series before calculating the annual means for each and averaging them into one index (SLH). Upwelling indices (Bakun 1973) were obtained from NOAA/PFEL (<http://www.pfel.noaa.gov/>) as monthly values for the points shown in figure 2 (UW a , where a stands for the point).

Four coastal areas, enumerated in figure 2, were used to estimate relative abundance of zooplankton, fish larvae species, and sardine and anchovy eggs and larvae. The data are from the CalCOFI database, and were kindly provided by Paul Smith. In the case of zooplankton (ZP n , where n stands for the area number shown in fig. 2), the index is the yearly averaged macrozooplankton displacement volume at all occupied stations in each area; the total number of different fish larvae species per year for each area is the second index (SP n). The annually averaged number of individuals per occupied station was used as an index for sardine egg abundance (SE n), sardine larvae abundance (SL n), anchovy egg abundance (AE n), and anchovy larvae abundance (AL n), after transforming each of these series by $\ln(x+1)$ to account for their log-normal distribution.

Longer series were obtained from Douglas (1976), who reports SST reconstructed time series for six coastal points based on tree-ring data (also shown in fig. 2). The series consist of quarterly anomalies; they were averaged for the year for each estimation point. Principal component (PC) analysis of the yearly averaged series readily separates two PCs: the first one captures 64.5% of the total variance, and is related to points north of Magdalena Bay, the coastal area of the CCS; the second (14.3% of the total variance) is linked to the subtropical variations at the southern tip of the peninsula. The PC1 of these series was used as an index.

All the half-century (1950 to present) indices were standardized and grouped by Ward's method (Ward 1963) with $(1 - \text{Pearson's } R)$ as a measure of distance; three groups were obtained. Averaged values were then calculated for each year, and smoothed by a 20-year Hamming window.

We were unable to find a single corresponding temperature time series for the last 2,000 years for comparison to sardine scale abundance, so we used four different temporal scales, associated with unequal scales of precision. First, we digitized figure 2 in Crowley 1998 to obtain a proxy of global temperature anomalies for the last two millennia, and used reconstructed global temperatures from Mann et al. (1999) for the last 1,000 years. We used the PC1 of coastal SST anomalies in Douglas 1976 as a proxy for the 1800–1900 period, and the average SST anomalies in the CCS for the 1900–2000 period.

The number of sardine scales in varved sediments of the Santa Barbara Basin is from Baumgartner et al. 1992, kindly provided by Paul Smith.

RESULTS

Half-Century Trends

Tree clustering separates three major groups (fig. 3):

- group 1 includes sardine egg and larval abundance at areas 2 (Punta Baja) and 3 (Sebastián Vizcaíno), macrozooplankton abundance at all areas, and upwelling at the southern areas (south of the Southern California Bight);
- group 2 incorporates all anchovy egg and larval abundance series at all areas, the number of fish larvae species at all areas, and sardine egg and larval abundance at the southernmost area (Golfo de Ulloa);

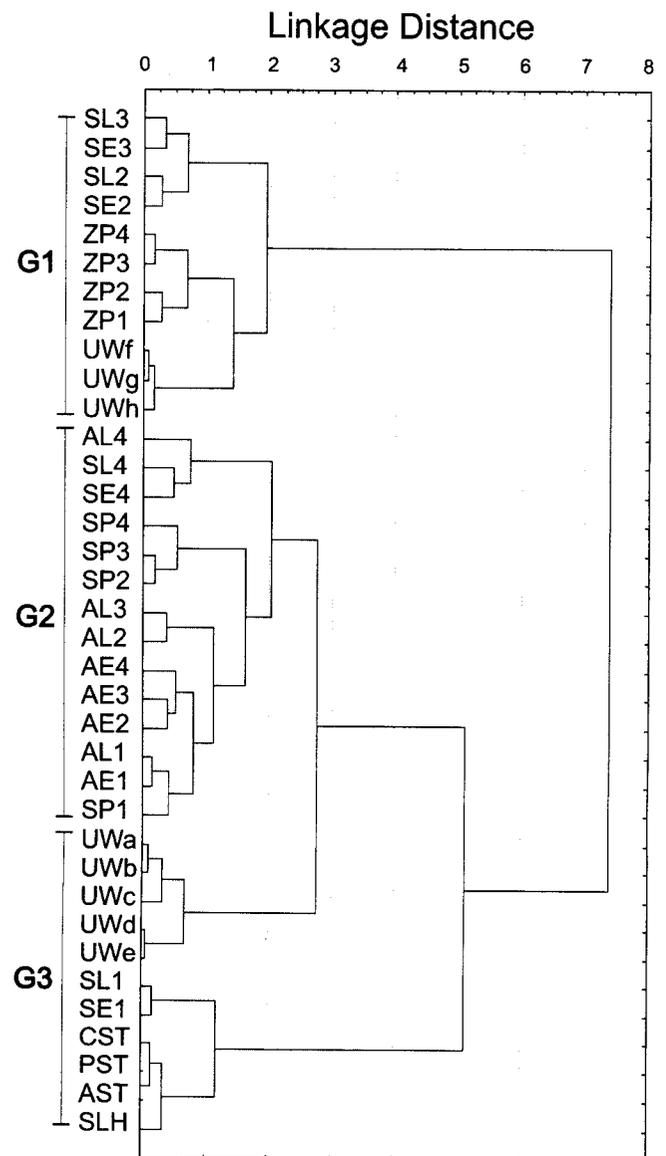


Figure 3. Tree diagram (Ward's method) of the 36 variables in the 50-year series. (See text for explanation of variables.)

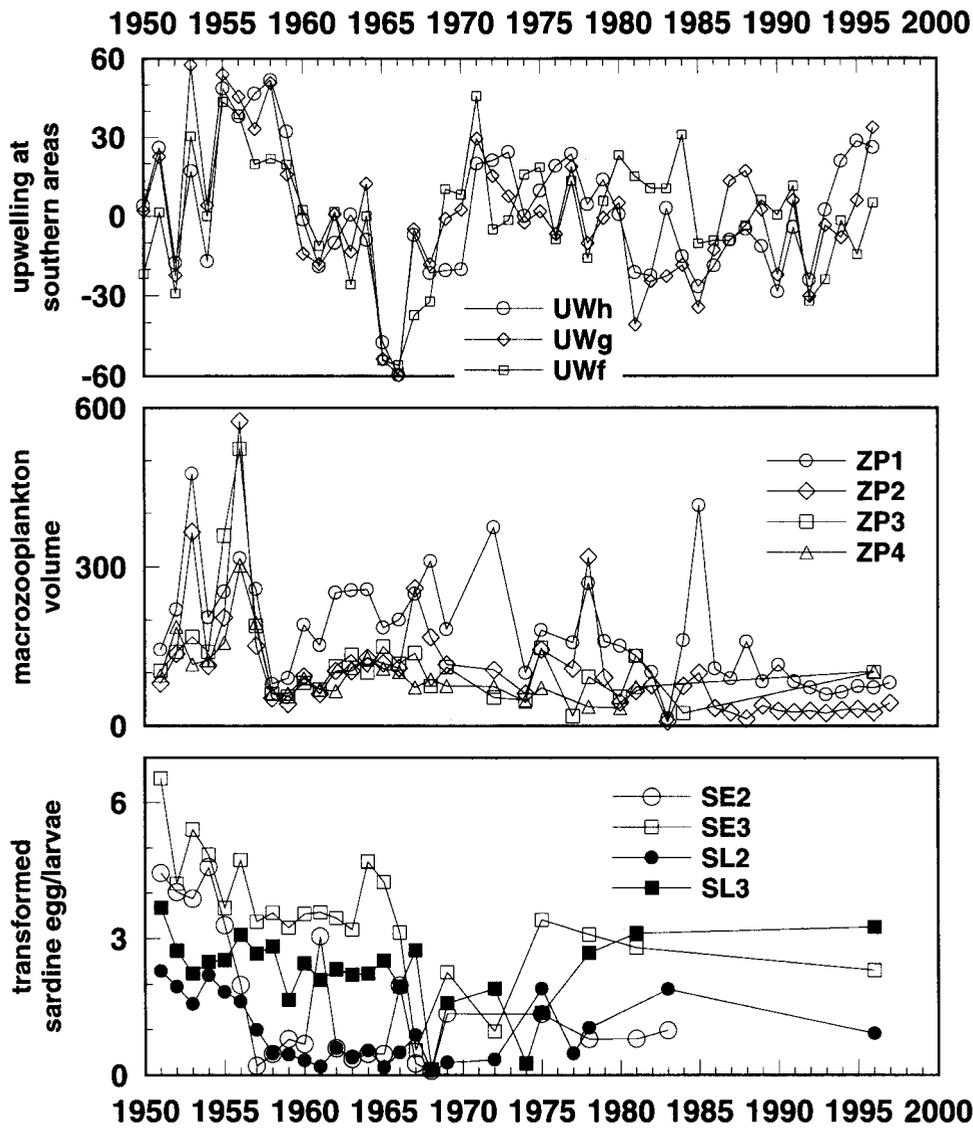


Figure 4. Half-century series group 1: yearly values of upwelling indices at the southern areas; macrozooplankton volumes and transformed number of sardine eggs and larvae at areas 2 and 3.

- group 3 encompasses all the AST, PST, and SLH series, plus sardine egg and larval abundance at area 1 (Santa Barbara).

The annual data for each group are shown in figures 4 (group 1), 5 (group 2), and 6 (group 3). The annual means for each group are shown in figure 7, together with their 20-year smoothed series. Although a large interannual and interdecadal variability exists, long-term trends are apparent: groups 1 and 3 are mainly opposed, G1 decreasing in the long term, while G3 increases; also, their interdecadal variations are contrary. Group 2 also shows large interannual and interdecadal variability. As for the long term, an increasing trend from 1950 to the mid-1970s changes to a decreasing trend since then.

Century-Long Variation

Figure 8 shows the mean yearly SST anomalies for the COADS quadrants shown in figure 2. There is considerable high-frequency interannual variation; the average year-to-year change is about 0.4°C, with a positive maximum of 1.3° and a largest negative value of -1.5°. The series shows nearly average values at the onset of the century, a cool period after 1906 lasting until roughly 1940, leveled fluctuating anomalies until the mid-1970s, and a sustained warm period since then. There are some clearly consistent multiyear warming and cooling episodes.

Reservations have been expressed about using COADS data before the 1950s; MacCall (1996) has de-

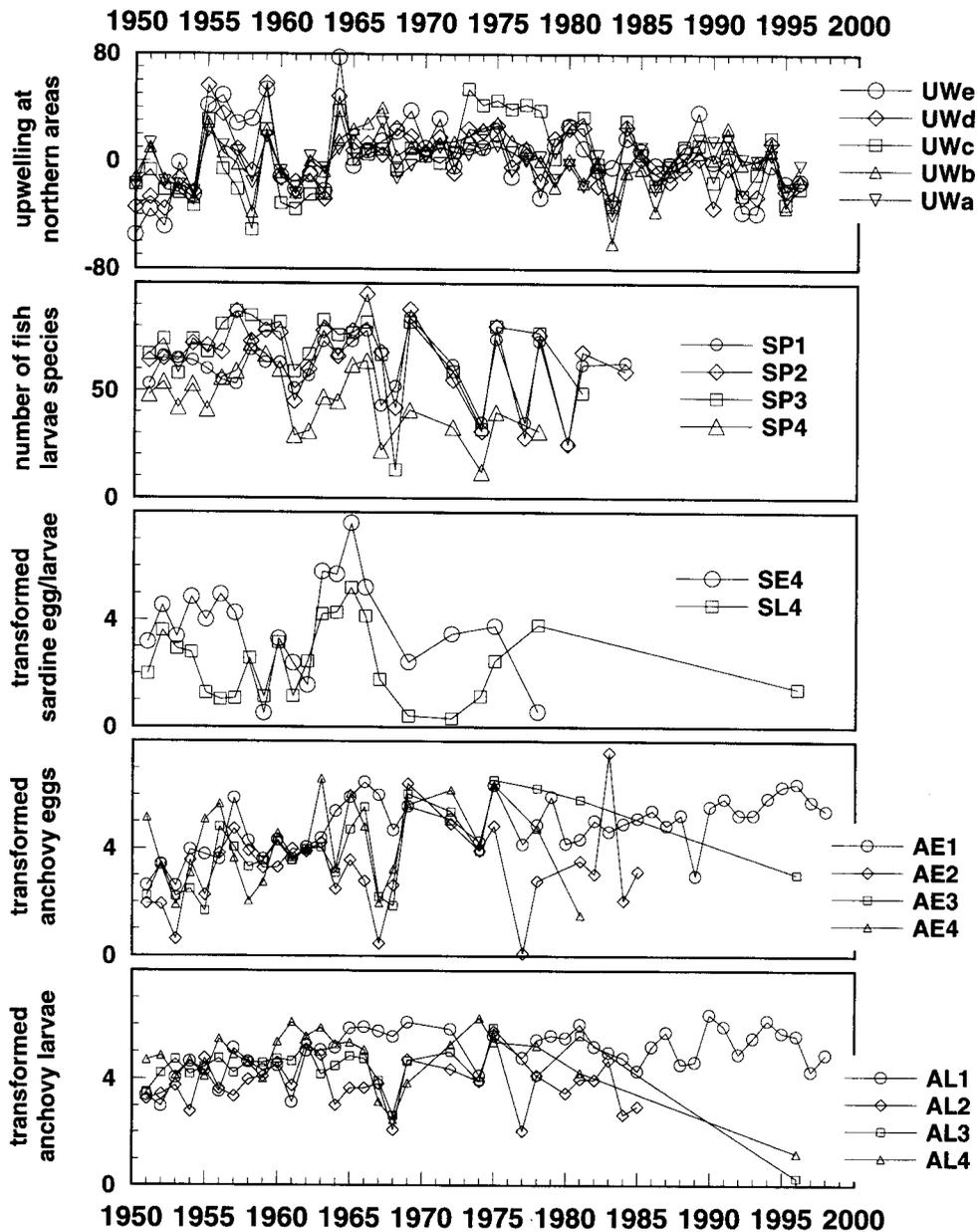


Figure 5. Half-century series group 2: yearly values of upwelling indices at the northern areas; number of fish larvae species at all areas, transformed sardine egg and larvae number at area 4, transformed anchovy eggs at all areas, and transformed anchovy larvae at all areas.

scribed some of them. In essence, the concern is based on gaps in the individual quadrant series due to incomplete sampling, which might bias averaging procedures. Figure 9 shows the number of quadrants with a nonzero value per year throughout the century; it is evident that the cool period coincides with poor coverage. The question is whether—if sampling were systematically biased due to, for instance, the colder, temperate portion being more intensively sampled than the warmer subtropical region—this difference would bias the average. Since the

point is not a trivial one, we used a number of criteria to increase the confidence in the series.

First, the lower average temperatures from the mid-1910s to late 1940s do not seem to be a consequence of incomplete sampling at warmer areas, since the procedure to estimate SST anomalies precludes geographic bias, being calculated for each individual quadrant and then averaged. The only possible drawback would be that each region had different trends.

However, all of the series are significantly ($p < 0.05$)

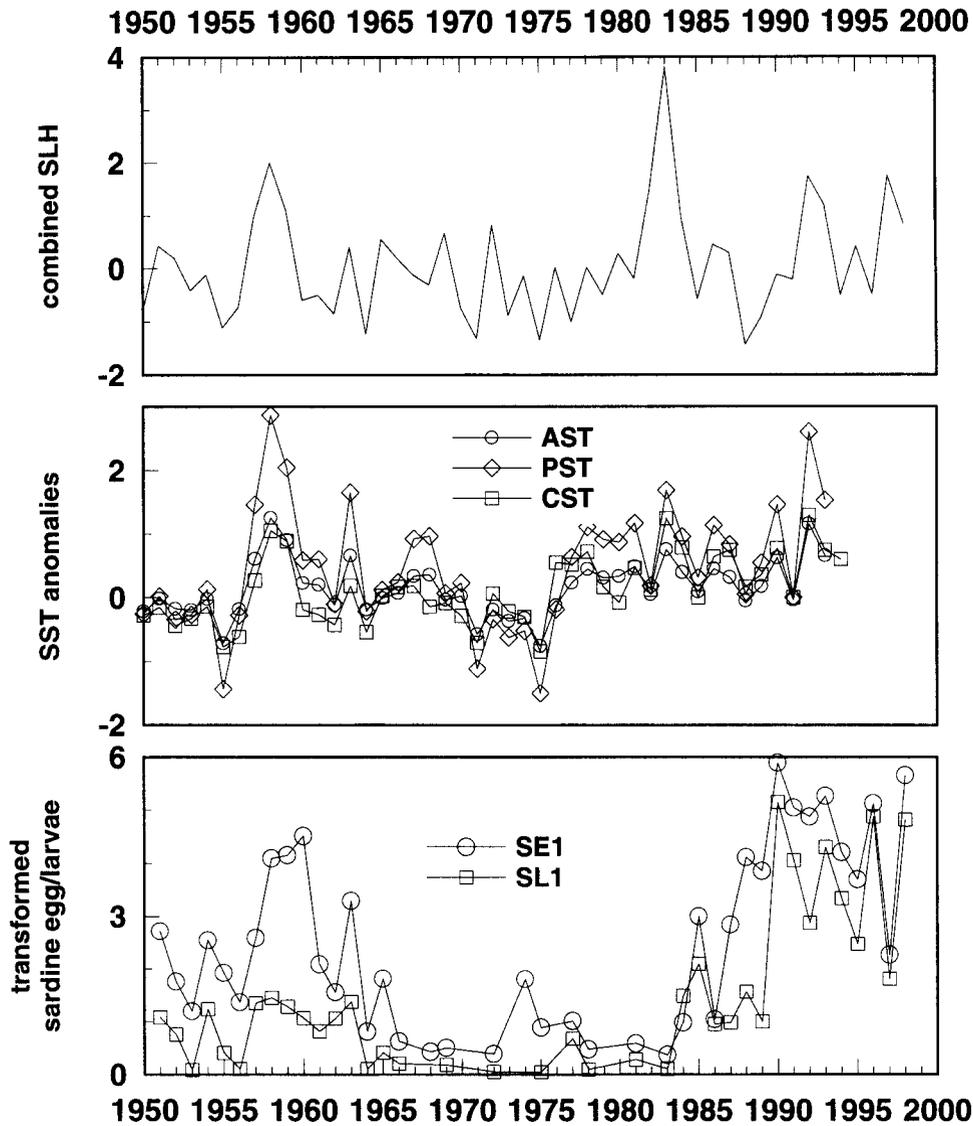


Figure 6. Half-century series group 3: combined sea-level height, sea-surface temperature series, and transformed number of sardine eggs and larvae at area 1.

correlated with each other, except for only two quadrants (22° – 24° N, 120° – 122° W, in 22% of the cases, and 26° – 28° N, 118° – 120° W, in 9% of the cases), and these are among the least represented in time, so no major bias should be expected from this factor.

Completeness per quadrant (the actual number of observations divided by the maximum possible number) for the full century and for the 1914–28 period (the one with poorest representation; fig. 9), is shown in figure 10. Transects conform to the horizontal divisions of the COADS area shown in figure 2. There is always rather good latitudinal coverage, particularly in the coastal areas, so no related bias from this source should be expected either.

Factor loadings for PC1 of the SST anomalies for

each of the 76 COADS quadrants are shown in figure 11. The California Current limits, digitized from Lynn and Simpson (1987) are indicated by dashed lines for comparison. There is geographic coherence in the fact that higher PC1 factor loadings coincide rather well with the current itself.

Comparison to a number of similar interval and related time series, all shown smoothed in figure 12, shows similar trends. The 10-yr Hamming window smoothed series are all significantly correlated ($p < 0.05$). The PC1 of all the series, excluding the SST anomalies estimated from the COADS quadrants, is displayed in figure 13, together with the global SST anomaly ($r = 0.7627^{**}$, $n = 94$).

Hubbs (1948) described a warm period during the

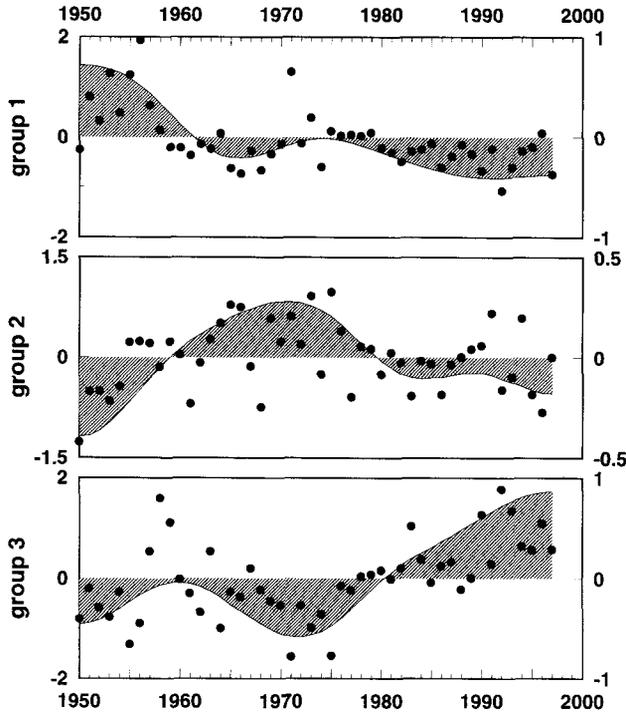


Figure 7. Means of the three groups in figure 3; annual values shown by circles, 20-yr. Hamming smoothed series as the hatched background line. Note the different scales.

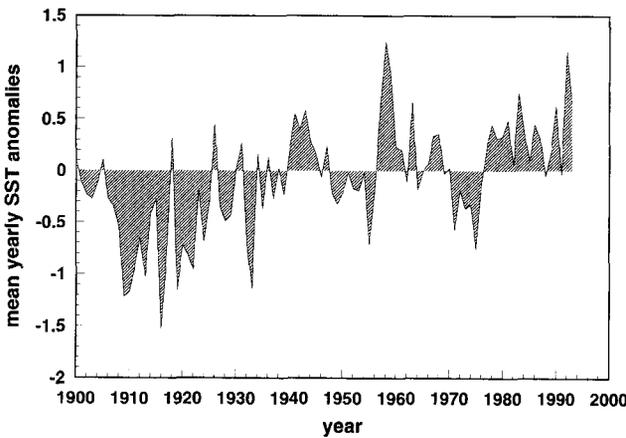


Figure 8. Yearly averaged SST anomalies for the COADS quadrants shown in figure 2.

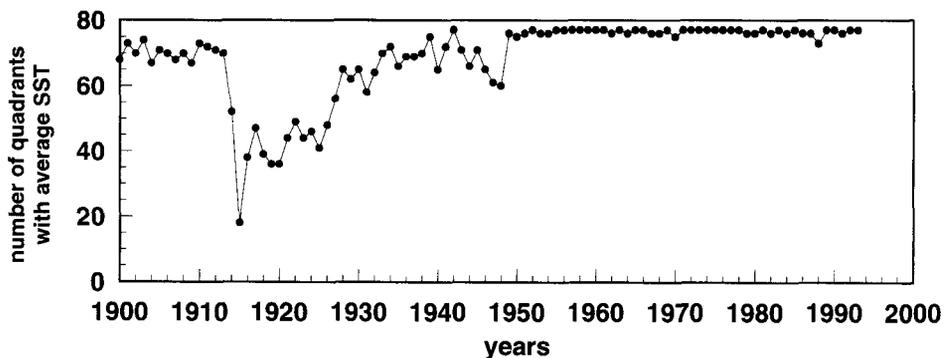


Figure 9. Number of COADS quadrants with nonzero value per year.

1850s–60s and a subsequent cooling until about 1910, after which there was a moderate reversion toward warmer conditions. Radovich (1961) stated that ocean temperatures were high during 1926, 1931, and 1941, and very low from 1948 through 1956. MacCall (1996) described a moderate and highly variable period from the beginning of the series (1920) to about 1940, a cold interval until 1976, and a warm period since then. Parrish et al. (2000) found an extensive cold period from 1908 to 1930 and warm intervals during 1931–47, 1958–61, and 1977–95. All four accounts agree well with the annual SST average anomalies series from the COADS database.

The low-frequency pattern shows cooling since the onset of the century until the first or second decade, then warming until the 1930s–40s, slight cooling until the mid-1970s (with a warming event during the late 1950s), and warming from then to the present.

Interannual Variation at Longer Time Scales

Series for the most recent two centuries appear in figure 14. The upper panel shows the 10-year Hamming smoothing of the PC1 (related to areas north of Magdalena Bay) of the coastal SST series from Douglas (1976) and number of sardine scales at the varved sediments of the Santa Barbara Basin described by Baumgartner et al. (1992) as a proxy for species abundance in 10-year intervals for an almost 1,000-year period. Starting at about 1830, a warming period is closely followed by increased sardine abundance, peaking during 1850–60, the time for which Hubbs (1948) described a warm period in the CCS. Rapid cooling afterwards also parallels a decline in sardine abundance, with a minimum in about 1880. An outburst of sardine abundance in 1890 corresponds to a very intense and sudden temperature increase at about the same time. The anecdotal accounts are not clear as to what happened between the recognized warm 1850s period and about 1910, the coolest year in the century-long series (see also MacCall 1996).

In the twentieth century, a low sardine abundance

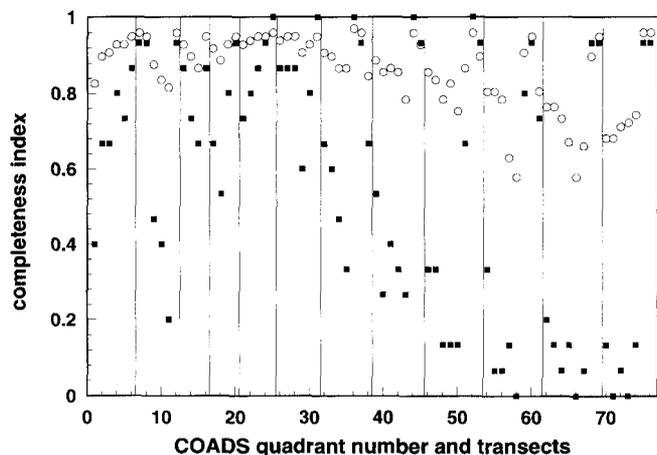


Figure 10. Completeness index: actual number of nonzero values divided by the maximum number: squares, the 1914–28 period; circles, remainder of the series. Vertical lines indicate the latitudinal transects shown in figure 2.

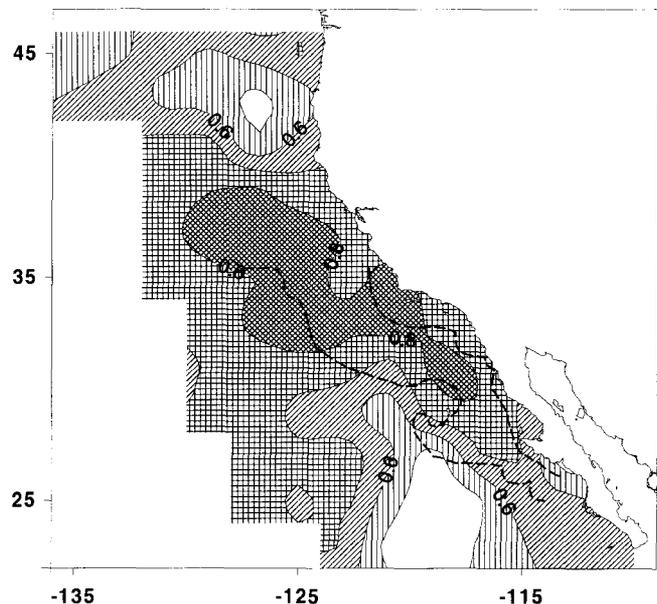


Figure 11. Spatial PC1 of SST anomalies in the 76 COADS quadrants. Approximate limits of the California Current, digitized from Lynn and Simpson 1987, shown as broken lines.

value about 1910 coincides with the lowest recorded temperature. The following population growth of sardine basically parallels the development and growth of the fishery, whose landings peaked about 1940, when sardine scales were already diminishing. The low abundance trend persists until the 1970s–80s, when a reversal seems to occur.

The full series of sardine scales at sediments is shown in the lower panel of figure 15; temperature proxies for the global temperature and the Northern Hemisphere are displayed in the upper panel.

Keeping in mind the uncertainty of the temperature

proxies, we suggest a number of gross characteristics of both series. First of all, there seems to be a correspondence between temperature and sardine abundance, as previously proposed (Lluch-Belda et al. 1989). It appears, however, that high sardine population abundance is related not so much to sustained warm temperatures as to periods of warming.

A long period of low abundance of sardine extended through the Little Ice Age (~1400–1900), but a particularly interesting event occurred during the mid-1400s: rapid cooling followed by intense warming. The warming phase was soon followed by an explosive increase in sardine abundance. This is an isolated event, immersed in a cool period.

DISCUSSION

Interannual change occurs at all time scales in the California Current system; even if high frequency is eliminated by smoothing, the remaining trends still change irregularly. The different length, coverage, and precision of the available data series make the search for patterns of change difficult and uncertain. Within the evident limitations of the present exercise, however, some blurred relations may yield interesting grounds for building a number of hypotheses about trends.

For the most recent 50 years, the CalCOFI database adds invaluable information about a great number of variables, of which we have only used a few. Nonetheless, their mode of change makes it possible to group them into three main patterns, as shown in figure 3.

It should be kept in mind that the trend, obtained by means of a 20-year smoothing window, makes the extreme years in the series depend on fewer points as they approach the beginning and end of the series; also, the smoothed filled line (trend) is exaggerated in the vertical scale, as can be seen in the right axis of figure 7. In general terms, only one of the groups (G1) shows a consistent long-term declining trend; the other two display fluctuating trends. Although these fluctuations in the last two groups seem basically to change on a decadal to bidecadal frequency, that of G2 begins low, increases to a maximum during the 1970s, and declines again; from this perspective, G2 is the only one that shows a trend reversal. Group 3 appears almost as inverse to G2, but also begins low. If not for the considerable effect of the 1957–59 ENSO, G3 would show a basically increasing trend.

In G1, upwelling in the southern areas, zooplankton volume in all areas, and sardine spawning in the central area fundamentally tended to decline from 1950 to 2000; the series is dominated by the very high values of the early 1950s, subsequent plummeting in the late 1950s, followed by a steady decrease. Upwelling would seem to be the dominant physical feature determining pro-

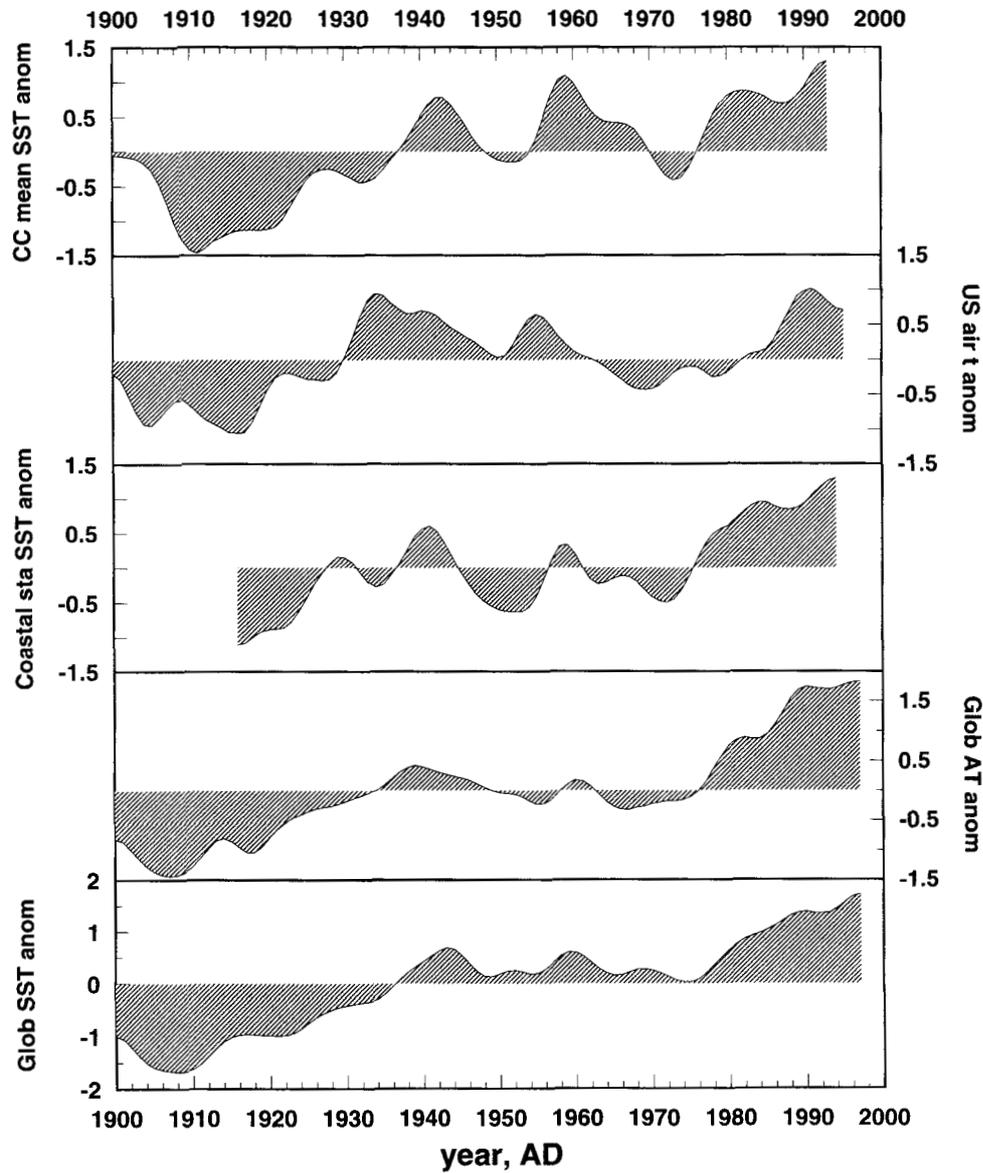


Figure 12. Yearly averaged SST anomalies in the 76 COADS quadrants; conterminous U.S. yearly air temperature anomalies; yearly averaged SST anomalies at coastal stations; global air surface temperature anomalies; and global SST anomalies; all series smoothed by a Hamming window of 10 terms.

ductivity; however, Bernal (1981) summarized earlier work that shows that zooplankton volume in the CCS is more related to southward advection than to upwelling. One possibility is that in these southern CCS areas the effect of advection gradually diminishes and upwelling becomes more determinant. While zooplankton volumes and upwelling decreased through the full 1950–97 period, sardine egg and larval data are interrupted in these areas after the mid-1970s. Nonetheless, they also diminished in the existing data period.

Conversely, AST, CST, PST, SLH, and sardine spawning in the northern area have been increasing, as shown

in G3 (fig. 6). The series show the signal of the 1958–60 warming event. Sardine spawning increase fits with previously proposed mechanisms (Lluch-Belda et al. 1991). Both warming (G3) and zooplankton decline (G1) match the findings of Roemmich and McGowan (1995).

On the other hand, in G2, upwelling north of Santa Barbara, anchovy spawning at all areas, and sardine spawning at the southernmost area (although the series is interrupted during the mid-1970s) tend to increase until the 1970s and decline afterwards. Unfortunately, upwelling is the only parameter recorded for all areas throughout the full period. Sardine spawning increase

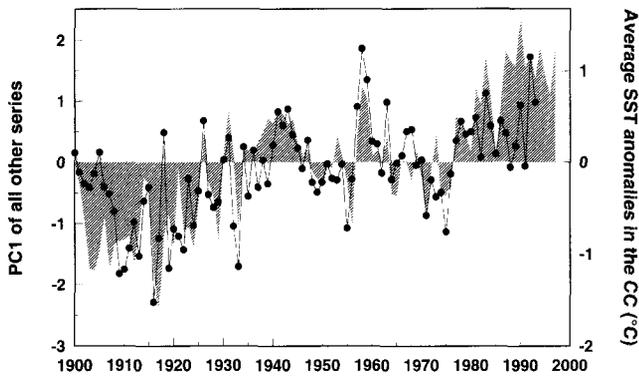


Figure 13. Yearly averaged SST anomalies at the COADS quadrants (shaded) and PC1 of all other series shown in figure 6.

matches previously proposed mechanisms for concentrating population at the equatorward limits during cool periods, but the series is too short to determine whether spawning declined afterwards.

Upwelling seems to show the regime shift signal. Hsieh et al. (1995) found upwelling trend reversals during the 1940s shift on a differential latitudinal basis, similar to what we have described here for the 1970s shift. Schwing and Mendelsohn (1997) showed a minimum in spring-summer SST off southern California about 1970 due to a temporal maximum in coastal upwelling, while similar SSTs off Baja California have risen steadily.

Anchovy spawning also shows the change in trend at all areas, but sardine spawning differentiates latitudinally.

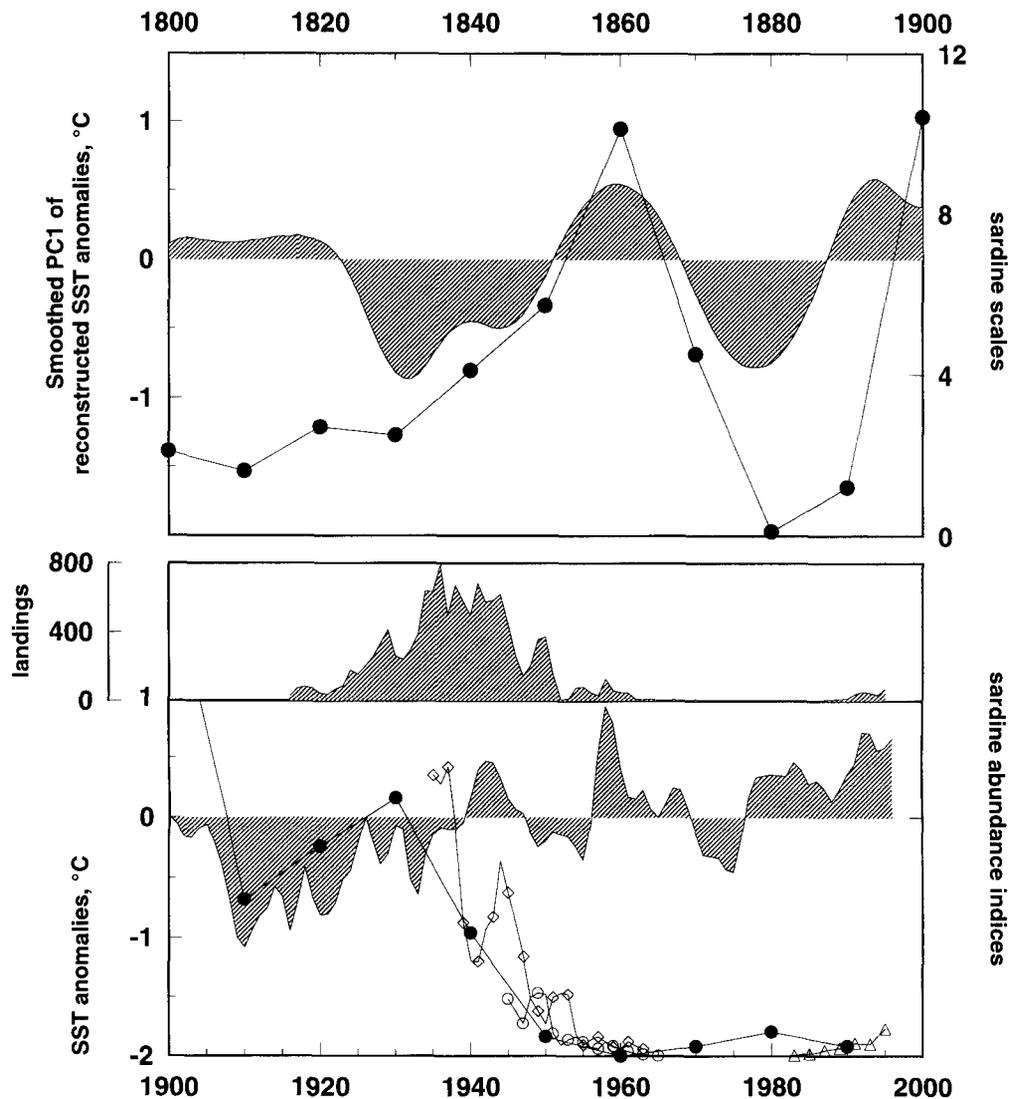


Figure 14. Upper panel: smoothed coastal reconstructed SST anomalies (shaded) and sardine scale number, 1800–1900; lower panel: yearly averaged SST anomalies at the COADS quadrants and various indices of sardine abundance: ● sardine scales at varved sediments (Baumgartner et al. 1992), ○ 2+ adult biomass (MacCall 1979), △ 1+ biomass (Deriso 1996), and ◇ spawning biomass (Jacobson 1995).

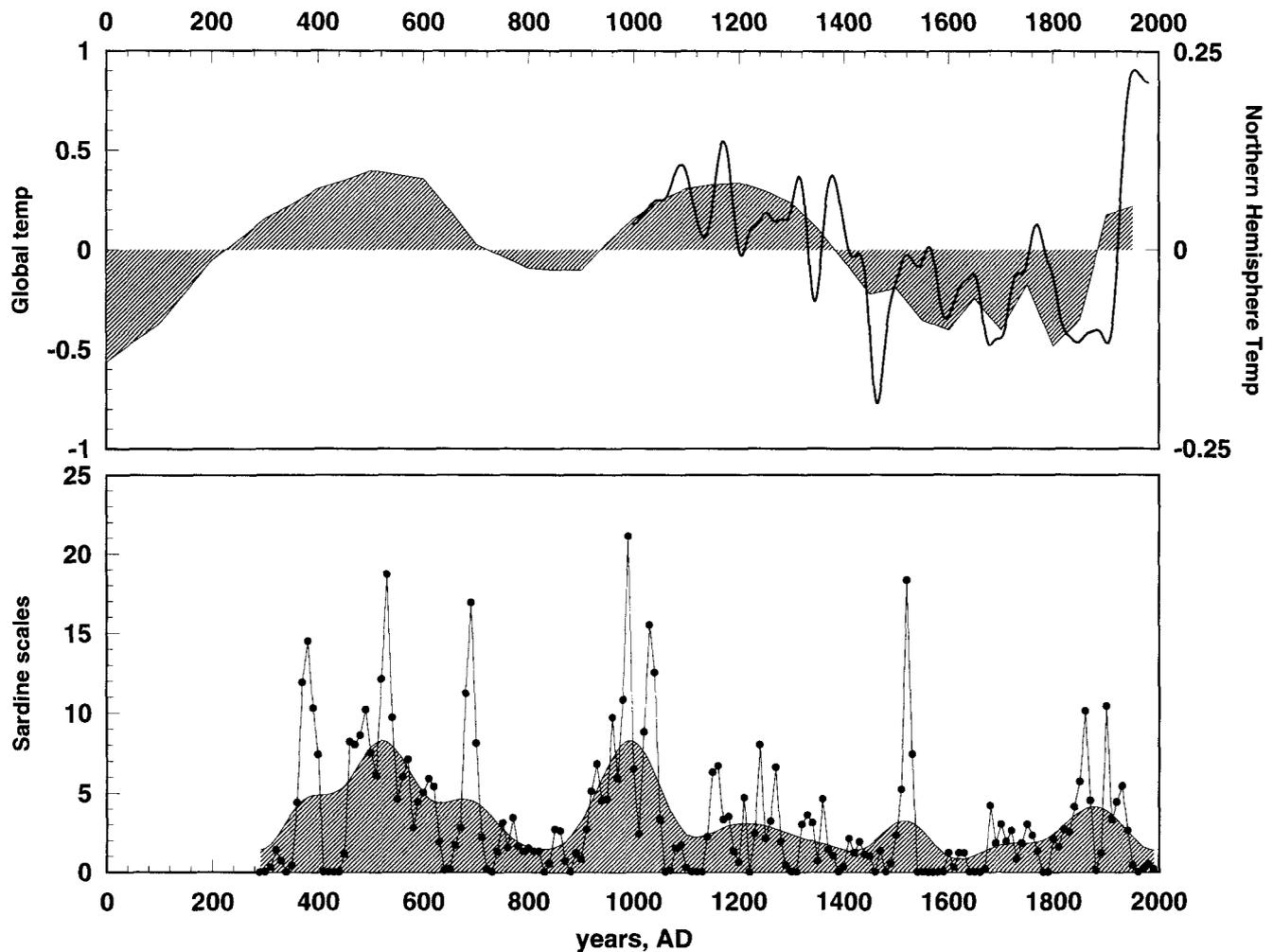


Figure 15. *Upper panel:* temperature proxies: global temperature anomalies in 50-year intervals (Crowley 1998, hatched line); Northern Hemisphere temperature anomalies (from Mann et al. 1999, line). *Lower panel:* sardine scale abundance at the Santa Barbara Basin at 10-year intervals, together with a 10-term smoothing.

This might support the idea that anchovies are more related to the California Current itself, while sardines have more of a coastal nature (Hernández-Vázquez 1994). A promising index, taking into account the coherence between different latitudes, is that of the number of larval fish species; unfortunately, the series extends only to the mid-1970s.

The shift in the mid-1970s looks like a trend reversal approximately coincident with the reported regime shift of 1976. Kerr (1992) showed an abrupt jump in several environmental variables between 1976 and 1977; we find a reversal of trend in the original nonsmoothed series, not a step, but this would depend on what kind of variable is being analyzed.

Turning to the century-long series, we suggest that figure 8 reasonably represents the basic shape of the SST anomalies during this period, as confirmed by a number of other series and anecdotal references. The series shows average temperatures at the beginning of the cen-

tury, a fast cooling period to the 1910s, and a warming trend peaking during the 1940s.

Afterwards, there was a cooling trend until the mid-1970s; the intense but brief warming resulting from the 1958–59 El Niño is evident in this series but did not change the trends, as described above for the 50-year period. The trend reversal occurred during the mid-1970s, and has persisted to the end of this series.

We thus suggest that there have been three trend reversals or regime shifts: about 1910+ \uparrow , 1940+ \downarrow , and mid-1970s \uparrow . The last two agree well with those proposed by MacCall (1996), Lluch-Cota et al. (1997), Mantua et al. (1997), Minobe and Mantua (1999), and Parrish et al. (2000). The first is dephased from that proposed by Mantua et al. (1997) around 1925, but agrees with the description of Hubbs (1948). Parrish et al. (2000) considered 1958–61 as a warm period.

If the above description is true, then we have been able to observe only one full cycle during the century,

extending between minima at 1910+ and the mid-1970s, or roughly 60 years. This period matches that described by Baumgartner et al. (1992) as the dominant signal in sardine scale abundance, and with periods discussed by MacCall (1996), Ware (1995), and Lluch-Cota et al. (1997). It also fits with the period suggested by Francis and Hare (1994), since their interval between shifts extends for about 30 years.

During the twentieth century (lower panel of fig. 14) sardine abundance increased until 1930, and then fell off. We suggest that this breakdown was facilitated by an intense fishery (landings data shown in fig. 14); if population abundance had followed previous patterns, it would have increased to the 1940s at least, as MacCall (1996) earlier proposed. The population began growing again after the mid-1970s, and this increase became apparent during the early 1980s.

Before 1900, however, the 60-year cycle seems to be one of several (figs. 14 and 15). A warm peak during 1860 coincides with the account of Hubbs (1948) and a maximum abundance of sardine scales; between then and 1910 anecdotal references seem contradictory as to the existence of an intense brief period (MacCall 1996), but both sardine scale abundance and reconstructed SST show a minimum during 1880 and a fast increase to about 1900. If this is correct, then the resulting cycle would be only about 40 years.

Even within the limited resolution (10 years) of the sardine scale abundance series, a sardine population buildup appears to be an explosive process, usually taking less than 40 years, but population collapses seem to be even more abrupt, mostly between 20 and 30 years. Baumgartner et al. (1992) showed that recoveries range from 20 to 70 years, 36 on average, while collapses average 30 years (20 to 50 years). Such outbursts are much more frequent and reach higher values during warm periods, but are also present during cool ones (e.g., about 1450). In the long perspective, sardines were at least two times as abundant before the onset of the Little Ice Age than afterwards, although there was some recovery during the 1800s.

Within this longer perspective, it becomes clear that the fundamental sardine abundance regimes are not those of warm or cool periods, but those of warming or cooling intervals. As Richard Schwartzlose (Scripps Institution of Oceanography, pers. comm.) suggested at the Scientific Committee on Ocean Research Working Group 98, it is the change itself that makes the difference: sardine populations begin growing explosively while it is cool, and start collapsing when the environment is still warm. In figure 15, the growing trend of the sardine population between A.D. 200 and 500, and the lapse from 900 to 1100 follows the warming trend, while declines occur during the cooling periods. Parrish et al. (2000) sug-

gested that the principal source of the biological bonanza in the CCS during the late 1970s lies in processes associated with the shift from one climate state to the other, not in the new state itself.

Changes in both population abundance and environmental temperature must result from some underlying process variations; we suggest that oceanic current patterns might be associated with such changes, as earlier proposed by several authors (Wooster and Hollowed 1995; Bakun 1996; Lluch-Cota et al. 1997), such as intensification/relaxation of the ocean gyres (Bakun 1996), diversion of flow (Trenberth 1990; Latif and Barnett 1994), etc.

The scales of variation discussed above, in spite of their very different precision, show some common features; warming and cooling periods seem to be the norm. Instead of prolonged cool or warm intervals, change seems to be continuous at every scale shown here, from millennia to years. Although we have often referred to sustained conditions as those that extend between crossings of the average, no single level is supported for a long time, whatever the scale. However, cooling or warming trends extend for decades and more. The CCS seems to be a huge subarctic/subtropical mixing area, permanently under the changing predominance of one environment or the other.

There is coherence between the analyzed scales and formerly described processes, particularly when dealing with biological indices. Even though the most detailed and potentially useful ones span only a few decades, those that may be related between time scales and to other series (such as sardine abundance and temperature proxies) show coherence in time and between parameters.

Temperature at the CCS is closely related to U.S. and global air temperature and other indices at the century-long scale; thus it seems reasonable to use global and Northern Hemisphere temperature proxies. At all analyzed time scales, sardine abundance and temperature maintain a direct but not causal relationship, which is consistent with previous results.

On the other hand, sardine abundance also appears to vary simultaneously with other biological and physical parameters, as becomes apparent in the short but detailed series. Thus it is not unlikely that sardine abundance variations in the long term are related to, at least, similar changes in the same parameters, suggesting that change is not exclusive to small pelagic fishes, but likely affects the whole ecosystem.

Regimes were first detected through their biological consequences (Hubbs 1948), as were their basic theoretical concepts (Isaacs 1976), global nature (Kawasaki 1983; Lluch-Belda et al. 1989), and persistence (Soutar and Isaacs 1969; Baumgartner et al. 1992). The most detailed report of a regime shift incorporated a consid-

erable number of biological indices (Kerr 1992). What has been difficult is finding the original sources of variation and the physical mechanisms through which they operate to produce biological change.

Looking at physical variability itself, Zhang et al. (1997) pointed out the inadequacy of characterizing periods solely on the basis of interdecadal regime shifts that become apparent only with the benefits of hindsight. They further stated that changes during the 1957–58 period were no less dramatic than those around 1976–77, the only difference being that the resulting warming persisted for only a few years.

Certainly, the AST series shows a more intense event during the late 1950s and early 1960s than during the early 1940s. The cooling phase of both looks similar and lasted about the same time. The 1957–60 event is considered a warm period by authors looking at physical parameters (Ware 1995; Wooster and Hollowed 1995).

In spite of all these similarities, authors working with the regime scale of change and basically using biological indices identify ~1940 as a regime shift, but not ~1957 (fig. 1). The latter change did not result in a sustained increase in sardine population, even though spawning intensified in the Southern California Bight during this lapse (Lluch-Belda et al. 1991).

The origin of regime variation is still obscure. Solar radiation, operating through phytoplankton production (Kawasaki 1983); changes in the spawning habitat due to temperature variations (Lluch-Belda et al. 1991) or current shifts (Kondo 1980; Watanabe et al. 1996; Wada and Jacobson 1998; Nakata et al. 2000); wind regimes and offshore advection (Parrish et al. 2000); upwelling and primary production (Kifani 1998; Yasuda et al. 1999); and intensification of ocean gyres (Bakun 1996; Lluch-Cota et al. 1997), among other changes, have all been proposed as the forcing mechanism. While most authors agree that sardines undergo large fluctuations on the decadal scale related to global climate, the question remains as to how individual stocks respond to common physical forcing in remote marine ecosystems (Matsuura 1999; Schwartzlose et al. 1999).

Ware (1995) discussed some global cycles related to thermohaline circulation and to solar cycle length, and concluded that there is no consensus about the origin of the VLF signal.

If regimes are global, their origin has to be either a very strong and persistent internal change to affect most oceans, or external. If external, then solar variations or planetary motion or both seem to be the obvious sources to look at. Even if a likely original source is found, there has to be a reasonable physical link between it and the biological indices described before it can be convincing. At this point, it appears to us that large-scale ocean current changes and associated atmospheric modifications

could be that link (Wooster and Hollowed 1995; Bakun 1996; Lluch-Cota et al. 1997; Parrish et al. 2000).

Regarding the possibility of forecasting, many uncertainties remain. Relatively short-term prediction (as derived from the long-term scales dealt with here) has been proposed by some authors. Lluch-Belda et al. (1992) suggested that a new shift occurred during the 1980s, when sardine abundance decreased in Japan and in the Humboldt Current and increased in the Benguela Current. Ware (1995) predicted that the transition to the next cool climate state could occur around 2001, but it should be noted that he was basically referring to decadal-bidecadal fluctuations and not to a long-term regime shift. MacCall (1996) cautiously speculated about the possibility that a transition to a cooler regime is likely in the next decade or so, based on biological indicators. Lluch-Cota et al. (1997), on the basis of their regime indicator series (RIS), suggested that a new global cooling trend could begin during the 1990s. Hare and Mantua (2000) found evidence for a regime shift about 1989.

Monitoring some biological indices still seems to be the most promising clue to regime shifts, looking for early warnings such as trend reversals in abundance, synchrony, species substitution, etc. Biological indices seem to more entirely integrate the full array of environmental changes associated with regime shifts than do physical parameters taken one or a few at a time. Even hindcasts seem uncertain when relatively few variables are taken into account (Zhang et al. 2000); however, some indices such as the PDO (Mantua et al. 1997) are proving very appropriate for nowcasting. Hare and Mantua (2000) suggested that closely monitoring ecosystem variations could make it possible to identify regime changes sooner than monitoring climate alone.

Although the potential value of being able to predict regime shifts is beyond question, it should be noted that long-term forecasting is still unreliable; regime cycles have been variable in the past and are likely to be so in the future. Global indices such as the ERVI (Klyashtorin 1998) are still based on previous behavior during relatively short periods and thus uncertain. Forecasting regime shifts and periods on a long-term basis still requires much work. Minobe (2000) states that the usefulness of an empirical forecast is significantly limited by the small number of events observed, and that nowcasts of regime shifts should be based on an understanding of their physical mechanisms. Hare and Mantua (2000) show that, even with retrospective analysis of ecosystem data, contemporary detection of regime changes is not yet possible.

ACKNOWLEDGMENTS

The original idea for these retrospective experiments was proposed by Warren Wooster and Patricio Bernal at

the Living Marine Resources Panel of the Global Ocean Observing System. This is also a much delayed aftermath of Scientific Committee on Ocean Research Working Group 98, which dealt with large fluctuations in sardine and anchovy populations; Alec MacCall has led the way in publishing derivatives of its results. Paul Smith provided many of the data used, and the orientation. Raymond S. Bradley kindly oriented us to paleoecological data. This paper had support from the Instituto Politécnico Nacional DEPI 988004 project and the Centro de Investigaciones Biológicas del Noroeste, S.C. (CIBNOR). DBLC is doctoral student at CIBNOR on scholarship (CONACYT 95344).

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FEEDING HABITS OF THE COMMON THRESHER SHARK (*ALOPIAS VULPINUS*) SAMPLED FROM THE CALIFORNIA-BASED DRIFT GILL NET FISHERY, 1998–1999

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ABSTRACT

The diet of common thresher shark (*Alopias vulpinus*) from U.S. Pacific Coast waters was investigated by means of frequency of occurrence, gravimetric and numerical methods, and calculating the geometric index of importance (GII) of prey taxa taken from stomachs collected by fishery observers from the California-based drift gill net fishery. Sampling was done from 16 August 1998 to 24 January 1999, a time when the California Current was undergoing rapid change from El Niño to La Niña conditions. Of the 165 stomachs examined, 107 contained food representing a total of 20 taxa, revealing a broader trophic spectrum than previously reported for this species. Of the identifiable items, northern anchovy (*Engraulis mordax*) was the most important in the diet (GII = 48.2), followed by Pacific hake (*Merluccius productus*; GII = 31.2), Pacific mackerel (*Scomber japonicus*; GII = 24.8), and Pacific sardine (*Sardinops sagax*; GII = 9.2). Of the invertebrates, squid (Teuthoidea, including *Loligo opalescens*; GII = 6.3), and pelagic red crab (*Pleuroncodes planipes*; GII = 6.6), were also important, especially numerically. For sharks collected north of 34°N latitude, hake was the most important identifiable species in the diet; northern anchovy was most important in the south, but was not identified in stomachs collected north of Point Conception.

INTRODUCTION

The Pacific Fishery Management Council recently included the common thresher shark (*Alopias vulpinus*) as a management unit species within the U.S. West Coast Highly Migratory Species Fishery Management Plan, now under development. This has prompted the need for biological information on life history, stock structure, feeding ecology, and essential habitat of this species to better assess stock status and harvest impacts. To date, little has been documented on its habitat requirements, and only anecdotal accounts are available on its feeding ecology off the U.S. West Coast.

The common thresher shark is a large, active, and strong-swimming shark that occurs in neritic and oceanic waters in subtropical and temperate seas worldwide

(Compagno 1984). It is epipelagic, gregarious, and cosmopolitan, and in the northeastern Pacific seems to be most abundant within 40 miles of shore (Strasburg 1958). Its known range extends from Clarion Island, Mexico, north to British Columbia; it is common seasonally from mid-Baja California, Mexico, to Washington state.¹ It is the leading commercial shark taken in California, where it is highly valued in the fresh fish trade (Holts et al. 1998). It is also sought by recreational anglers for its fighting ability as well as food value, especially in southern California. Patterns of observed catches and results of limited tagging suggest that it undertakes a seasonal north-south migration along the Mexico-U.S. West Coast, moving northward in summer, then returning to waters off Mexico in winter (Hanan et al. 1993).

Anecdotal accounts identifying prey items of this shark are scattered throughout the literature, but no comprehensive study of food habits has been undertaken. In California, as in other parts of the world (e.g., Spain; Moreno et al. 1989), *A. vulpinus* frequently occur in association with large schools of small fishes, and feed on them near the surface, often slashing the water with their whiplike tails, presumably to herd or disorient their prey. According to Compagno (1984), this shark also feeds on mackerels, bluefishes, clupeids, needlefishes, lancetfishes, and lanternfishes, as well as squids, octopuses, pelagic crustaceans, and (rarely) seabirds. Although he provided no supporting data, Bedford (1992) reported that, unlike other pelagic shark species off California, the common thresher shark does not appear to be an opportunistic feeder, but rather feeds almost exclusively on northern anchovy (*Engraulis mordax*). California fishermen have reported finding salmon in the stomachs of large individuals (W. Rendernick, Monterey, Calif., pers. comm. 2/28/98). In the eastern North Atlantic, Pascoe (1986) examined teleost otoliths from the stomach of a 264 kg female, and concluded that the stomach had originally contained at least 28 scad (*Trachurus trachurus*), 6 whiting (*Merlangius merlangus*), and a single mackerel (*Scomber scombrus*).

¹Smith, S. E., R. C. Rasmussen, D. A. Ramon, and G. M. Cailliet. Biology and ecology of thresher sharks (family:Alopiidae). In Sharks of the open ocean, E. Pikitch and M. Camhi, eds. MS submitted to Blackwell Scientific Publications.

We examined and analyzed the stomach contents of common thresher shark collected by drift gill net observers off California, and compared diets between size/age classes, seasons, and general catch locations.

MATERIALS AND METHODS

Sampling at Sea

Stomach samples were collected from three common thresher shark size groups by federal fishery observers aboard commercial drift gill net vessels operating off California and southern Oregon during the 1998–99 August through January fishing season. Because sampling time and freezer space are limited aboard these vessels, and to maximize sampling for small fish in the under-sampled inshore areas, observers were instructed to collect stomachs according to the following protocol:

1. size group = <100 cm fork length (up to ~200 cm total length, or young-of-year), up to 10 stomachs per trip;²
2. size group 101–160 cm FL (200–300 cm TL, or juveniles/subadults), up to 5 stomachs per trip; and
3. size group >160 cm FL (over about 300 cm TL, or adults/large subadults), up to 5 stomachs per trip.

Samples were excised at sea; esophageal and pyloric ends were secured with plastic cinch ties; and the stomachs were bagged, labeled, and frozen. Data on set and haul time, water depth, sea-surface water temperature, location, fish size, sex, and maturity state were recorded.

Processing in the Laboratory

Stomach samples were thawed, tamped with absorbent paper to remove excess water, and weighed full. Contents were then removed, and the empty stomach was weighed to determine the overall weight of the contents. Materials and slurry were rinsed and sorted with a series of screen sieves with mesh sizes 9.5 mm, 1.4 mm, and 0.5 mm for ease in rinsing mid-sized food boluses without losing some of the smallest items, such as fish otoliths. Percentage of stomach fullness (0–100%) was estimated visually as a broad gauge of relative fullness. The degree of prey digestion was estimated as follows:

1. Fresh: head, body, skin, and most fins intact, although some individuals may be in pieces (i.e., bitten on capture);
2. Intermediate: body and most flesh intact; fins, scales, and some or all skin may be digested;
3. Intact: skeleton from head to hypural plate or body/mantle/carapace intact, or easily reconstructed to obtain standard length measurements;

4. Unmeasurable body parts only: parts cannot be reconstructed to obtain standard measurements, but higher taxon or species group still identifiable;
5. Digested: identifiable only to a very general high-level taxon; and
6. Fully digested: unidentifiable material; slurry.

Prey items were then separated, identified to lowest possible taxonomic level, and enumerated, measured (to nearest mm, standard length) and weighed (to the nearest 0.1 g), when possible. Fish otoliths and squid beaks were counted in pairs, with the highest count representing the minimum number present. Weights were recorded by taxon groups (not individually), while lengths of all intact individuals within a taxon were measured.

Content data were pooled for all stomachs (all strata combined) and analyzed by prey taxa for relative measures of prey quantity (RMPQs) as follows: percent numeric occurrence (%N), percent weight (%W), and percent frequency of occurrence (%F) of food items. The value %N = the number of individuals of one prey taxon divided by the total number of all prey individuals $\times 100$; %W = weight of one prey taxon divided by total weight of all prey $\times 100$; and %F = number of stomachs containing prey of one taxon divided by total number of stomachs that contained any prey items $\times 100$. Empty stomachs and certain small incidentally ingested organisms, slurry, and detritus were not used in calculating percentages or indices.

Cumulative prey curves were constructed to determine whether an adequate number of specimens overall or in subsamples had been collected to describe diet (e.g., Hurtubia 1973; Cailliet et al. 1986; Gelsleichter et al. 1999; Yamaguchi and Taniuchi 2000). The order in which stomachs were analyzed was randomized 10 times, and the mean number of new prey species was cumulated consecutively in order of the stomachs examined. In this type of sample-size analysis, presence of an asymptotic relationship indicates that the number of stomachs analyzed is sufficient to represent the diet of a particular predator, and that enlargement of the sample beyond the point of curve stabilization would cause no further increase in trophic diversity (Hurtubia 1973).

Measure of prey quantity (RMPQ) values were used to calculate the geometric index of importance (GII), as developed by Assis (1996). The GII is based on a multivariate and multidimensional approach similar to principles used by Mohan and Sankaran (1988) for defining their two-dimensional diet indices. Summarizing Assis (1996), the degree to which a predator consumes each prey category is represented by vectors (V_i) along orthogonal axes in space, where $i = 1$ to n , as many orthogonal axes as the number of RMPQs used. The magnitude of each vector is the value of each RMPQ.

²Young sharks in this size group are usually taken only in certain areas and not in association with larger thresher sharks.

Any number of measures of prey quantity can be used (e.g., three RMPQs would occupy a cubic space; if $n > 3$, the space would be hypercubic). For a given prey category j , the GII is found by calculating a resultant vector P of magnitude $|P|$ that essentially unites all RMPQ vectors, where

$$|P_j| = \left(\sqrt{\sum_{i=1}^n (V_i)^2} \right)_j \quad (1)$$

A reference vector D is defined to represent maximum prey utilization (e.g., 100% V , 100% F , 100% N), where its magnitude $|D|$ would then be defined as

$$|D| = 100 \times \sqrt{n} \quad (2)$$

For prey type j , the GII is defined as the component of P along D . Thus it measures the degree of approach to complete utilization of that prey type, reducing the n dimensional space to one dimension, and originating a natural ranking of prey according to the magnitude of the projected prey vectors. After certain algebraic steps (Assis 1996), this component is found as

$$GII_j = \frac{\left(\sum_{i=1}^n V_i \right)_j}{\sqrt{n}} \quad (3)$$

where GII_j = index value for the j th prey category; V_i = the vector for the i th RMPQ of the j th prey category; and n = the number of RMPQs used in the analysis.

To examine differences in diet between mature- and immature-sized fish, northern and southern fishing areas, and fish caught early and late in the fishing season, the data were pooled into the following subgroups, and 2×5 contingency table analyses were carried out to determine whether consumption of the leading five diet items varied significantly in frequency and number among the subgroups. Only these two RMPQs were considered for this exercise; weight was not tested because of the extensive range of measurement values (in grams) and because of its general dependence on digestive state.

1. Sharks collected north of latitude 34°N , and sharks collected south of 34°N , all seasons combined.
2. Sharks collected August–October, and sharks collected November–January, all latitudes combined.
3. Presumed adult sharks >159 cm FL, and juvenile sharks ≤ 159 cm FL, all seasons and latitudes combined.

Finally, we compared results of our overall GII analysis with an analysis of the same RMPQ values using the index of relative importance (IRI, Pinkas et al. 1971). The IRI can be calculated as

$$\text{IRI} = (\% \text{ number} + \% \text{ weight}) \times \% \text{ frequency of occurrence.}$$

In comparing the two indices, we examined only the difference in relative ranking of the suite of prey types for each method, not the individual magnitude of index values, which is not comparable. To better graph and visually compare these proportional differences, we divided the IRI arbitrarily by 60 to equalize the vertical scale of the two indices.

RESULTS

A total of 165 stomach samples was collected from 48 trips by drift gill net vessels fishing between 16 August 1998 and 24 January 1999, from the California-Mexico

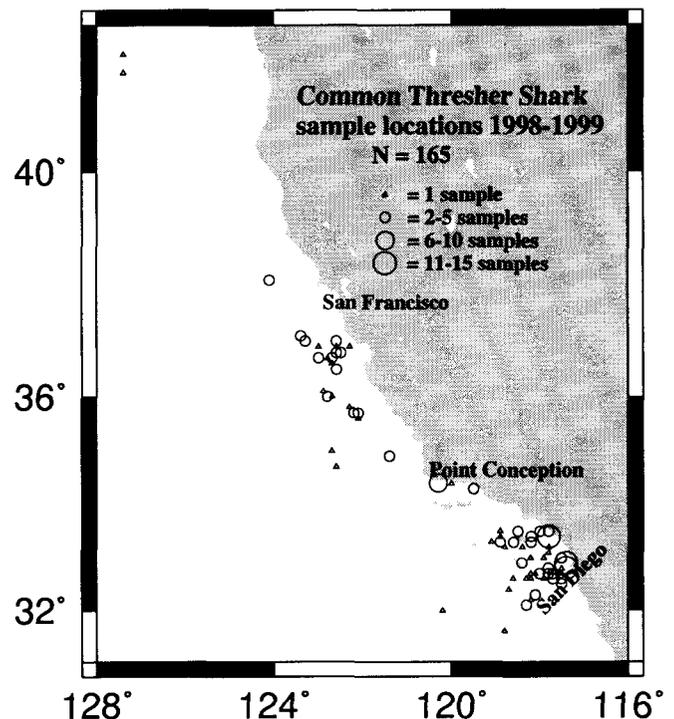


Figure 1. Collection locations for common thresher shark stomach samples, 1998–99.

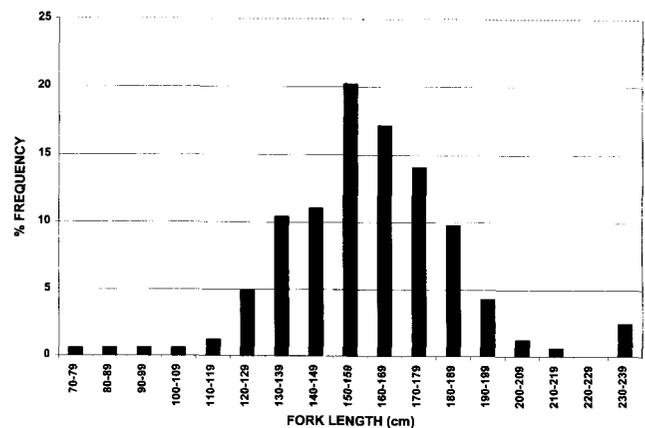


Figure 2. Length-frequency distribution of common thresher sharks sampled in the diet study.

TABLE 1
 Qualitative and Quantitative Prey Composition of the
 Common Thresher Shark (*Alopias vulpinus*) along the California-Oregon Coast

Prey species	W	%W	N	%N	F	%F	GII	IRI
Unidentified Teleostei	3,139.1	17.48	698	47.13	69	64.49	74.51	4,166.44
Northern anchovy, <i>Engraulis mordax</i>	5,409.7	30.12	472	31.87	23	21.49	48.18	1,332.09
Pacific hake, <i>Merluccius productus</i>	1,646.9	9.17	166	11.21	36	33.64	31.19	685.48
Pacific mackerel, <i>Scomber japonicus</i>	4,442.8	24.73	21	1.42	18	16.82	24.81	439.86
Pacific sardine, <i>Sardinops sagax</i>	714.0	3.97	66	4.46	8	7.48	9.18	63.07
Pelagic red crab, <i>Pleuroncodes planipes</i>	22.6	0.13	14	0.95	11	10.28	6.55	11.01
Louvar, <i>Luvanar imperialis</i>	1,784.3	9.93	1	0.07	1	0.93	6.31	9.30
Unidentified Teuthoidea	15.7	0.09	10	0.68	6	5.60	6.38	4.27
California barracuda, <i>Sphyræna argentea</i>	313.8	1.75	4	0.27	4	3.74	3.32	7.54
<i>Sebastes</i> spp.	1.2	0.01	8	0.54	4	3.80	2.46	2.09
Jack mackerel, <i>Trachurus symmetricus</i>	389.0	2.17	2	0.14	2	2.80	2.41	6.44
Market squid, <i>Loligo opalescens</i>	21.2	0.12	9	0.61	3	1.87	2.04	1.36
White croaker, <i>Genyonemus lineatus</i>	0.3	0.00	2	0.14	2	1.87	1.16	0.26
Unidentified Crustacea	0.3	0.00	2	0.14	2	1.87	1.16	0.26
California grunion, <i>Leuresthes tenuis</i>	0.2	0.00	2	0.14	2	1.87	1.16	0.25
Pacific butterfish, <i>Peprilus simillimus</i>	61.0	0.34	1	0.07	1	1.87	0.77	0.76
<i>Gonatus</i> sp.	0.5	0.00	1	0.07	1	0.93	0.58	0.07
Queenfish, <i>Seriphus politus</i>	0.2	0.00	1	0.07	1	0.93	0.58	0.06
Unidentified Octopoda	0.1	0.00	1	0.07	1	0.93	0.58	0.06
Pacific sanddab, <i>Citharichthys sordidus</i>	0.1	0.00	1	0.07	1	0.93	0.58	0.06

W = weight in grams; N = number; F = frequency; GII = geometric index of importance; IRI = index of relative importance. A total of 107 stomachs containing food and 58 without food were examined.

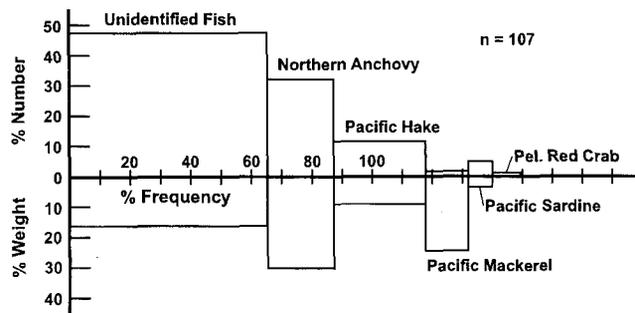


Figure 3. Graphical representation of diet using RMPQ values % weight, % frequency of occurrence, and % number of the six major prey items (IRI diagram).

border north to off the California-Oregon border (fig. 1) over water depths 27 to 2,250 fm (49 to 4,115 m). All specimens were collected in the morning hours from nets set overnight, which is the general practice of the drift gill net fishery.

Sampled sharks ranged in size from 79 cm to 237 cm FL (lengths were available for 163 sharks out of 165) with 82.8% between 130 and 189 cm FL (fig. 2).

Of the 165 stomachs examined, 107 contained food representing a total of 20 taxa (table 1), indicating a broader trophic spectrum than previously assumed for this species. The category "unidentified teleost" was the most important in number, frequency, and weight (table 1, fig. 3), with a GII value of 74.5 (fig. 4). Most of the food items (82%) were in advanced digestive states 5 and 6.

Overall, of the food items identified below the phylum level, northern anchovy (*Engraulis mordax*; GII =

48.2) was the chief prey, followed by Pacific hake (*Merluccius productus*; GII = 31.2), Pacific mackerel (*Scomber japonicus*; GII = 24.8), and Pacific sardine (*Sardinops sagax*; GII = 9.2; fig. 4). Of pelagic invertebrate prey, market squid (*Loligo opalescens*) and pelagic red crab (*Pleuroncodes planipes*) also contributed to the diet.

The distribution of the stomach collection locations for major diet items revealed certain patterns (fig. 5). Northern anchovy was important overall, especially in the Southern California Bight. North of 34°, Pacific hake appeared to be the most important food item, followed by unidentified teleosts, unidentified squid, and northern anchovy. Rockfishes (*Sebastes* spp.) and a variety of other species also contributed to the diet in the north. Anchovy, sardine, and pelagic red crab were not identified in the diet of fish collected north of Point Conception (34°27'N, 120°28'W).

Cumulative prey curves all described a general asymptotic relationship (figs. 6 and 7), but only two reached full asymptotic stabilization (fig. 7A, D). Thus our sample sizes may not have been sufficient to describe the overall trophic diversity of this predator's diet, but are adequate to describe the main prey items, since all curves exhibited a pronounced "knee," leveling off at about 40–70 samples.

Two-way, 10-cell contingency table analyses of the five major identifiable diet items of fish captured north of 34°N ($N = 28$) versus those captured south of that latitude ($N = 119$) showed the diet to differ significantly for frequency (chi-square = 12.1; d.f. = 4; $p < 0.05$) and also for number (chi-square = 43.8; d.f. = 4; $p < 0.05$).

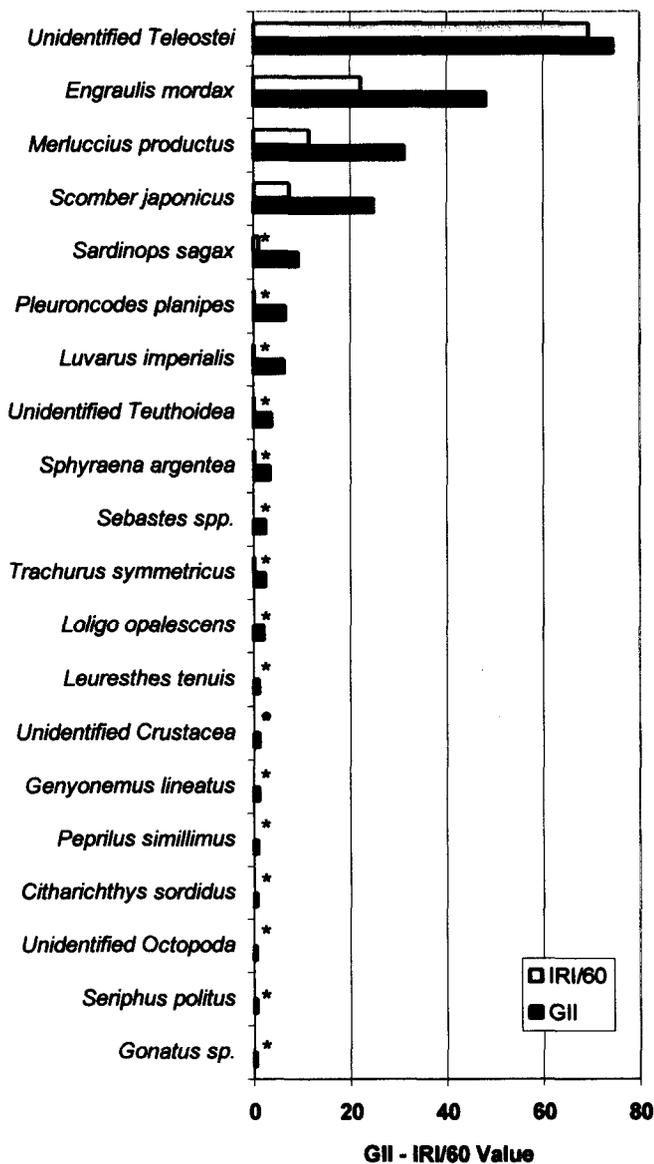


Figure 4. Results of geometric index of importance (GII) and index of relative importance (IRI) analyses for the 20 prey categories ($N = 107$ sharks). The IRI is divided by 60 to equalize vertical scale. * denotes positive values. See also table 1.

Diet differences in samples collected during the first half of the fishing season (Aug.–Oct., $N = 88$) and the second half of the season (Nov.–Jan., $N = 61$) were also statistically significant for frequency (chi-square = 16.3; d.f. = 4; $p < 0.05$) and for number (chi-square = 260.0; d.f. = 4; $p < 0.05$).

For the diet/predator size analysis, insufficient samples were available to partition the data into the three initially targeted size groups, so the data were lumped into two size categories: immature-sized sharks (≤ 159 cm FL, $N = 59$) and mature-sized sharks (> 159 cm FL, $N = 46$). No significant overall diet differences were observed between the two size categories for frequency of

occurrence of the top diet items (chi-square = 2.48; d.f. = 4; $p > 0.05$), but there was a statistically significant difference in total numbers consumed (chi-square = 14.9; d.f. = 4; $p < 0.05$). Although anchovy was important in number for both groups, it ranked far higher for juvenile fish (< 159 cm FL, ~ 0 –5 yrs old), which consumed fewer hake and Pacific mackerel than did adults (≥ 159 cm FL; 5 years and older).

Comparison between the GII and IRI analyses (table 1 and fig. 4) showed the order of ranking to be very similar, but secondary- and tertiary-ranked diet items were proportionately more important in the vector-based GII analysis than in the IRI analysis.

DISCUSSION

The samples were taken during a transitional period when the physical and ecosystem structure of the California Current region was changing rapidly from El Niño to La Niña conditions. According to Hayward et al. (1999), winter and spring of 1998 were periods of strong El Niño conditions. Indeed, the presence of pelagic red crab in the diet seemed to indicate lingering warm-water conditions, since this species is normally found to the south, off Baja California, Mexico. But by fall of 1998, El Niño effects had waned, finally changing to cool-water conditions during the winter–spring of 1998–99 (Hayward et al. 1999).

Our findings confirm the importance of northern anchovy in the diet of the common thresher shark off southern California, but also suggest that the diet may be more varied and opportunistic than previously reported for California waters (Bedford 1992). Warm-water conditions, especially during the first part of the season (Hayward et al. 1999), may have been a contributing factor in the greater diversity of prey items, but we have not yet analyzed comparative data from a more “typical” year. Higher than average water temperatures throughout the 1990s have been implicated in a concurrent decline in anchovy abundance off California, just as the recent transition to La Niña conditions has been associated with a subsequent increase in anchovy numbers (Hayward et al. 1999). But although northern anchovy appears to be a preferred prey, especially among juveniles, our study indicates that the common thresher shark can also consume a diverse diet. Pacific hake is important north of the Channel Islands and Point Conception, where larger and older thresher shark individuals are thought to migrate or congregate in spring and early summer (Bedford 1992). Because Pacific hake also migrate northward in spring (Saunders and McFarlane 1997), it is possible that these two migrations could coincide.

We recognize that diet differences with size, season, and area were complicated by fleet dynamics during the sampling period, which imposed an overlying pattern

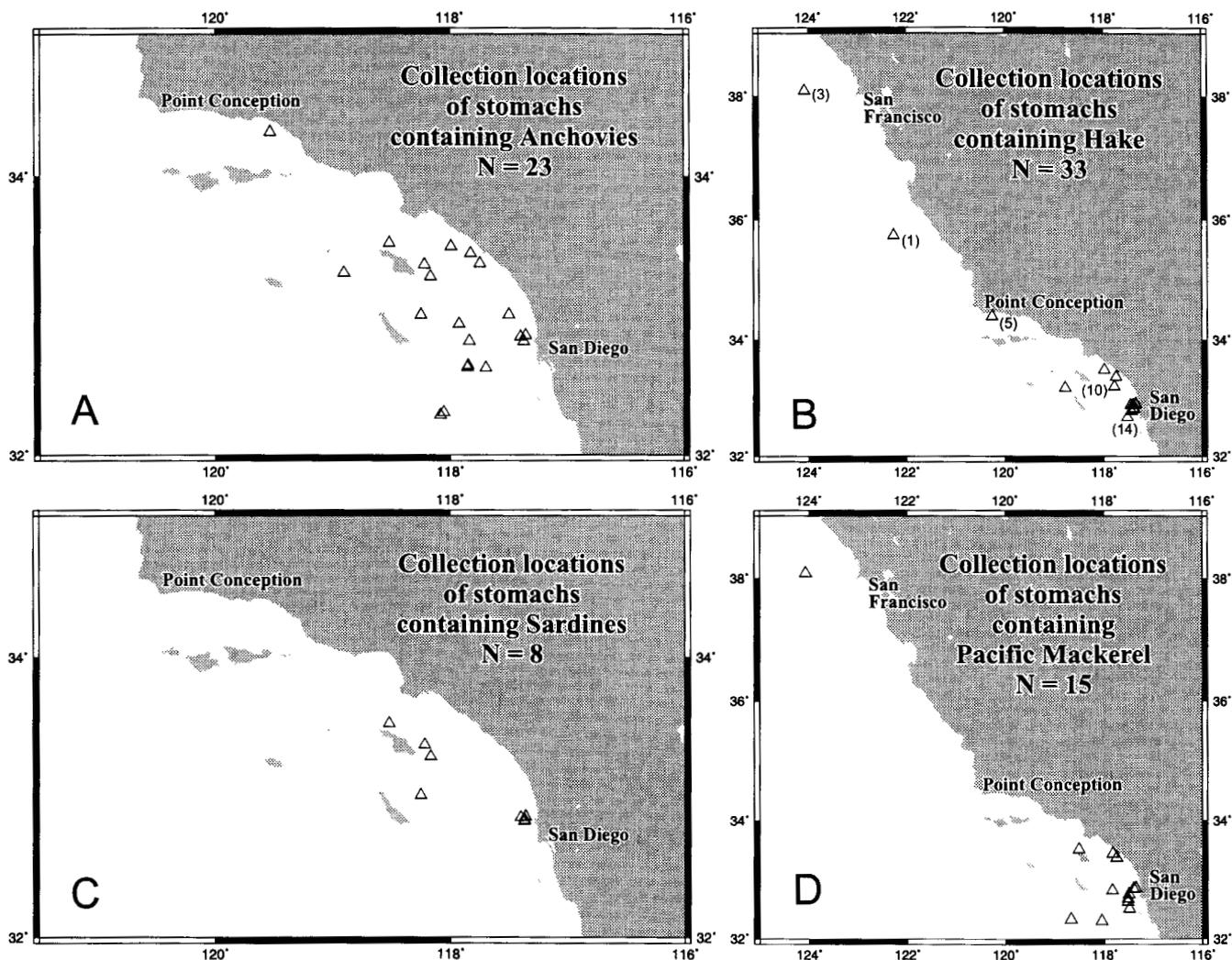


Figure 5. Distribution of the four major diet items by sampling location: A, northern anchovy, B, Pacific hake, C, Pacific sardine, and D, Pacific mackerel. (No anchovy or sardine were found in stomachs north of Point Conception: 34°27'N, 120°28'W.)

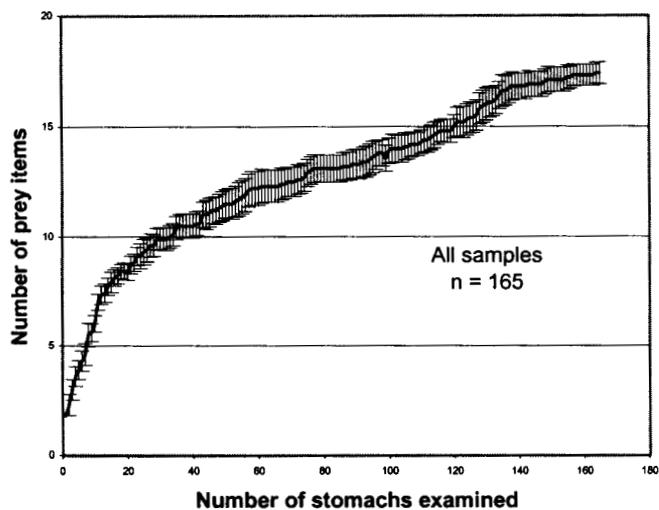


Figure 6. Randomized cumulative prey curve for overall *Alopias vulpinus* diet sample. Mean values are plotted; error bars represent \pm SE.

of collection times and areas. According to L. Enriquez (NMFS Drift Net Observer Program, Long Beach, Calif., pers. comm., 9/2000), in the 1998–99 fishing season, most samples from the August–October period were taken after the large boat fleet (boats most likely to accommodate observers) had shifted north of Point Conception. Most samples taken in the second half of the season (November–January) were collected south of Point Conception after the fleet moved south to the Southern California Bight. Thus, early season samples were collected mostly in the north, and late season samples primarily in the south. Nonetheless, diet differences for fish caught in the north early in the season and fish caught in the south later in the season appear to be real. And analyses of the cumulative prey curves indicate that our sample sizes were large enough to adequately capture an accurate profile of at least the major diet items of *A. vulpinus* as examined in the various treatments.

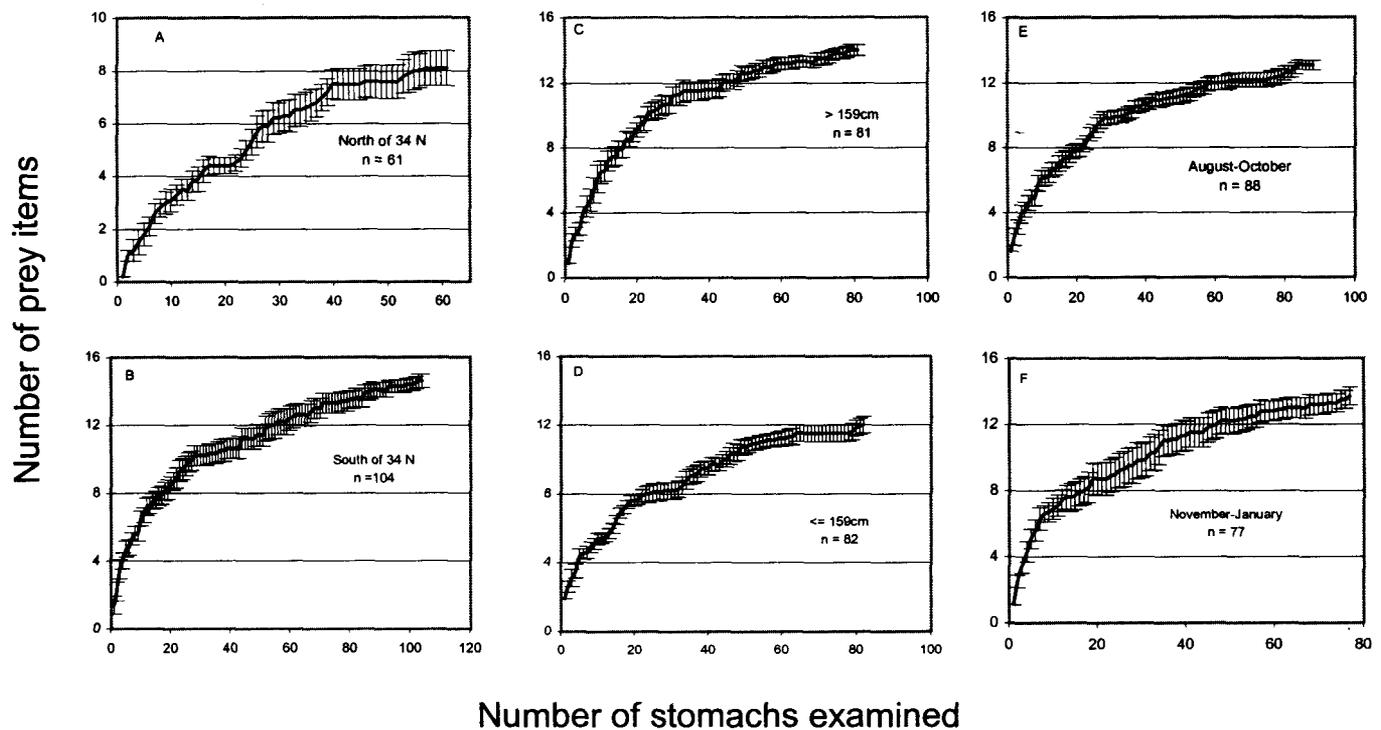


Figure 7. Randomized cumulative prey curves for analyses by area, predator size, and season: A, north and B, south of 34°N; C, large (>159 cm FL) and D, small (≤ 159 cm FL) *A. vulpinus*; E, Aug.–Oct. and F, Nov.–Jan. collection periods. Mean values are plotted; error bars represent \pm SE.

No conclusions can be drawn about diel feeding, because the period of time fish spent in the net before being sampled is unknown. That 82% of food was in an advanced state of digestion was not too surprising, considering the overnight duration of the sets.

This study applies a relatively new methodology (Assis 1996) for interpreting the overall relative importance of various diet items. Another recent example of its application is the work of Duarte and Garcia (1999), who used the GII to describe the diet of the mutton snapper (*Lutjanus analis*). Authors of fish dietary studies have long emphasized that each of the commonly used measures of prey quantity has limitations, each biased toward different aspects of the diet (Hyslop 1980; Cortés 1997). As Cortés (1997) points out, for this reason, many have chosen to use a simple compound index to rank prey, combined with some graphic representation of the relative measures of prey quantity. An example is the IRI developed by Pinkas et al. (1971). However, as Assis (1996) contends, these indices tend to be heterogeneous and produce results difficult to compare. Additionally, we feel that their logic and meaning are unclear, making interpretation of results difficult.

On the other hand, the GII analysis treats each measure of prey importance as a distinct orthogonal vector, combines them into a resultant vector, and then solves for its component along a reference diagonal that represents maximum prey utilization. From the resulting

geometry, the GII can be directly related to the degree of specialization in feeding on a particular prey type. Although technically this aspect is best expressed by the % GII (Assis 1996, eq. 8), the absolute GII itself (as presented in this paper and in eq. 7 of Assis 1996) differs only by a constant, thus the same relative ranking of importance or specialization among prey types (the most important feature) is found with either calculation. Although development of the GII is a welcome improvement, we also stress that any study of fish feeding should always include basic data summaries of all measures of prey quantities, because these data are crucial for application to ecosystem models and comparative diet studies.

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RECRUITMENT OF THREE SPECIES OF JUVENILE ROCKFISH (*SEBASTES* SPP.) ON SOFT BENTHIC HABITAT IN MONTEREY BAY, CALIFORNIA

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ABSTRACT

A number of ecologically and economically important species of rockfishes recruited to soft benthic habitats in Monterey Bay, California, during 1995–96. *Sebastes elongatus*, *S. saxicola*, and *S. levis* were the most abundant and, although caught throughout the depth range (40–100 m) of our survey, had highest densities from 60 to 100 m. Densities of *S. elongatus* and *S. saxicola* were greater than that of *S. levis*. Peak settlement followed ocean upwelling. Size–frequency analysis indicated that, once settled, juvenile rockfish ontogenetically moved toward adult depths. Growth rates ranged from 0.17 to 0.32 mm/d, with growth declining during months of highest sea-surface temperature. Peaks in distribution of back-calculated birthdates corresponded with periods of increased upwelling. Significant emigration from the sampling area occurred during the onset of winter storms.

INTRODUCTION

At least sixty-two species of rockfishes (*Sebastes* spp.) inhabit waters off the Pacific coast of North America (Eschmeyer and Herald 1983). Most of these species are important in both commercial and recreational fisheries. A major problem in managing rockfish resources is the difficulty in predicting year-class strength of these populations (Mearns et al. 1980). Studying the magnitude and timing of recruitment (defined in our study as the time of settlement of pelagic juvenile rockfish to benthic habitats) of young-of-the-year (YOY) fishes, and the processes that affect their survival, may be critical for understanding and predicting the relative size of the year-class when it enters the fishery.

Rockfishes exhibit unique reproductive and early life-history characteristics. Fertilization occurs internally, embryos develop within paired ovaries, and larvae are released into the water column 1–2 months after fertilization (Boehlert and Yoklavich 1983; Eldridge et al. 1991; Moser and Boehlert 1991). Larvae and pelagic juveniles of many rockfish species live in the upper 100 m

of the water column (Lenarz et al. 1991; Larson et al. 1994) for one to several months before settling to benthic habitats (Boehlert 1977; Moser and Ahlstrom 1978; Moser and Boehlert 1991).

Once settled, juvenile rockfish move gradually over several years into adult habitats (Love et al. 1991). Although abundance varies tremendously from year to year, numbers of older, pelagic juveniles have been significantly correlated with the abundance of settled juveniles, indicating decreased mortality during late pelagic and benthic stages (Ralston and Howard 1995; Adams and Howard 1996). Thus, a close relationship may exist between year-class strength and the number of juveniles that survive to the benthic stages.

Seasonal and annual changes in environmental conditions, such as timing and intensity of upwelling, are thought to influence survival of young rockfishes (Mearns et al. 1980; Larson et al. 1994; Ralston and Howard 1995). Upwelling centers are located just north of Monterey Bay at Point Año Nuevo and to the south at Point Sur (Breaker and Broenkow 1994; Rosenfeld et al. 1994). Upwelling is generally characterized by high nutrient concentrations, low temperatures, and offshore transport. While Parrish et al. (1981) hypothesized that offshore transport could be detrimental to the survival of early pelagic stages of fishes in the California Current, others have suggested that upwelling might benefit larval and juvenile rockfish through increased food resources and decreased predation by nearshore predators (Ainley et al. 1993; Larson et al. 1994; Yoklavich et al. 1996).

The influence of ocean conditions on interannual variation in juvenile rockfish abundance can be evaluated by comparing indicators of ocean conditions with the distribution of birthdates of fishes that survive the pelagic stage. Birthdate distributions have been estimated by subtracting age from the date of collection (Yoklavich and Bailey 1990; Woodbury and Ralston 1991; Yoklavich et al. 1996). These birthdate distributions for surviving juveniles can be compared with the time of spawning as predicted from the literature or from early larval surveys. Corresponding environmental conditions can be examined for possible influence on survival and growth of rockfishes during their early developmental stages.

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Several studies have examined rockfish recruitment to rocky bottom and kelp beds in Monterey Bay (Anderson 1983; Hoelzer 1988; Carr 1991; unpubl. data from D. VenTresca, Calif. Dep. Fish and Game, 20 Lower Ragsdale Dr., Monterey, CA 93940). Rockfish recruitment to soft benthic habitats has been documented in southern California (Boehlert 1977; Mearns et al. 1980). Approximately 80% of Monterey Bay is shallower than 100 m, and most of this area is soft-sediment habitat (Eittreim et al., in press). This habitat may be important for the recruitment of some rockfish species, but recruitment to this habitat has not previously been examined.

The 1996 amendments to the Magnuson-Stevens Fishery Conservation and Management Act (16 U.S.C. 1801 et seq.) require the description and identification of essential fish habitat (EFH), defined as those waters and substrata necessary for fish to spawn, breed, feed, or grow to maturity, as well as the implementation of measures to conserve and enhance this habitat. For many species, identifying EFH is difficult because of a lack of scientific information about habitat utilization. In order to fulfill the EFH mandate for rockfishes, habitat-specific information for all species and life stages is needed.

The purpose of this study was to describe spatial and temporal patterns in recruitment of dominant species of newly settled rockfishes to soft benthic habitats within Monterey Bay, California, and to examine growth and survival of these species. Specifically, we (1) determined species composition of juvenile rockfish on soft sediments; (2) analyzed spatial patterns in distribution of juvenile rockfish density and size; (3) assessed the timing and magnitude of rockfish recruitment to soft benthic habitats during 1995; (4) determined age and growth of the three dominant species during the benthic juvenile stage; and (5) interpreted birthdate distributions of these three species in terms of corresponding oceanographic conditions during the parturition period.

MATERIALS AND METHODS

Collections

Monterey Bay is located along the central California coast between 36.5°N and 37°N (fig. 1). The Monterey submarine canyon divides the bay more or less evenly into northern and southern sectors.

Fishes were collected with a small otter trawl (bridle length of 22.9 m, mouth width of 8.3 m, body mesh size of 3.8 cm, and cod-end mesh size of 1.0 cm) deployed from the RV *Ed Ricketts* on soft seafloor sediments in Monterey Bay. The mesh size of our otter trawl is efficient at sampling fishes as small as 19 mm (NMFS unpubl. data). Each tow lasted approximately 20 minutes. Sampling began in March 1995 and continued

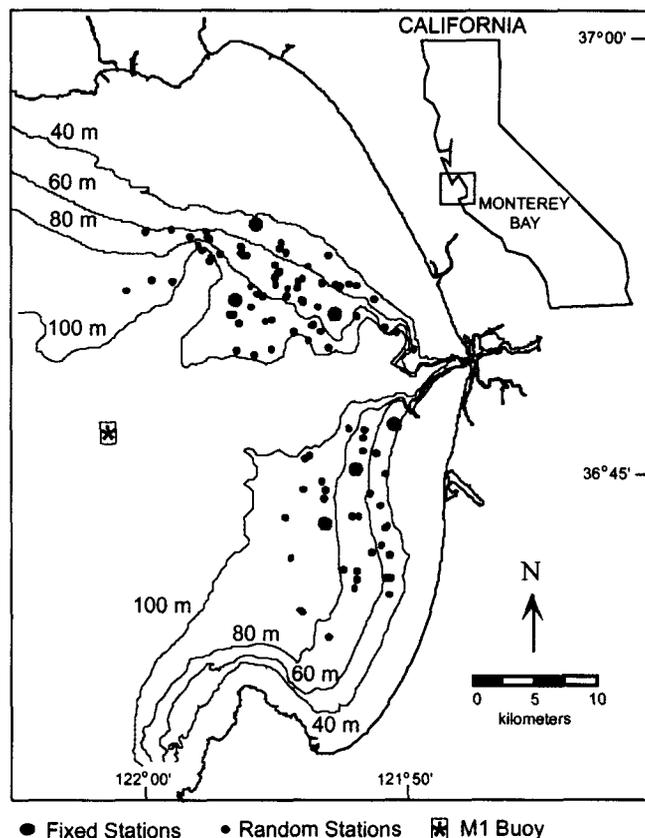


Figure 1. Otter trawls were used to sample juvenile rockfish almost weekly at stratified random and fixed stations between March 1995 and February 1996 in Monterey Bay, California. The M1 buoy is the source of sea-surface temperature data obtained from the Monterey Bay Aquarium Research Institute.

weekly, as weather permitted, through February 1996. Sampling stations were located within three depth strata: 40–60 m, 60–80 m, and 80–100 m (fig. 1). Minimum and maximum depths were based on gear constraints. Depth was stratified to ensure that the entire range was sampled and to facilitate comparisons of fish density among depths. Random samples were collected to evaluate spatial variations in abundance and size of rockfishes; samples at fixed stations were used to describe temporal changes in these variables. Locations for random stations, one per depth stratum, were determined before each weekly sampling. Six fixed sampling stations (two within each depth stratum) were determined prior to the first collection, and were sampled repeatedly throughout the survey period.

Fifty-six tows were completed in the 40–60 m depth stratum (30 at fixed stations, 26 at random stations); 72 tows were completed in the 60–80 m depth stratum (36 each at fixed and random stations); and 69 tows were completed in the 80–100 m depth stratum (30 at fixed stations, 39 at random stations).

All rockfishes (*Sebastes* spp.) were identified to species by means of a guide by Laidig and Adams (1991).

Standard length (SL) was measured to the nearest millimeter. Ages were determined from subsamples of sagittal otoliths of *S. elongatus* (greenstripe rockfish), *S. saxicola* (stripetail rockfish), and *S. levis* (cowcod) with techniques described by Stevenson and Campana (1992). Subsamples represented fishes from all months of sampling and the entire size range.

Daily growth increments in a thin frontal section of the otolith were enumerated at 1000 \times magnification with a compound microscope. Counts were made along the longest and clearest path from the nucleus to the otolith edge. The otoliths were read twice, with results from the first read unknown for the second read. There was a high degree of ageing precision and reproducibility for all three species as determined with the average percent error (APE; Beamish and Fournier 1981), coefficient of variation (CV), and index of precision (D; Chang 1982; see fig. 8).

Fish length and age data were fit to growth models by means of Systat (1992). We chose the Gompertz growth model because it best describes fish growth during early life stages, and has been used to describe juvenile growth in other rockfish species (Laidig et al. 1991; Woodbury and Ralston 1991). For *S. saxicola*, larval age data from Laidig et al. 1996 were included in the Gompertz model to help define the lower portion of the growth curve. The nonlinear Gompertz model was forced through a given size at parturition (4.5 mm for *S. elongatus*, 5 mm for *S. saxicola* and *S. levis*) as reported by Laidig et al. (1991). By using the inverse of the Gompertz equation, we determined ages for all individuals sampled within the size range of aged fishes, for each of the three species. Age was subtracted from the date of capture for each individual specimen to provide a distribution of birthdates for the surviving juveniles. We used a linear regression model to calculate a growth rate in mm/day for each species.

Distribution

All tows were standardized by area swept, that is (distance traveled) \times (net width), calculated as hectares (ha). In order to determine distance traveled, we recorded latitude and longitude by using a differential global positioning system (dGPS) immediately following the deployment of the trawl and again immediately before retrieval of the trawl. To maximize trawl contact with the bottom, and to insure accuracy and precision of distance estimates, constant vessel speed and direction were maintained as much as possible. Catch from each tow was considered one sample. Fish density (# fish/ha) at each station was plotted with a geographic information system (GIS) software program, MapGrafix (ComGraphix Inc, ©1994). Size data were plotted in histograms and reported as mean SL \pm one standard error.

Catch data from random stations were used to describe the spatial distribution of juvenile rockfishes in Monterey Bay. The Kruskal-Wallis nonparametric one-way analysis of variance was used to determine if there were significant differences in density with depth. A nonparametric analysis was necessary because of unequal sample sizes and nonnormal data. The Games and Howell modification of Tukey's pairwise comparison (Day and Quinn 1989) was used *post hoc* to test differences in means between depth strata. This method accounts for unequal variances and unequal sample sizes. We compared standard lengths of fishes from random stations among depth strata by using the Kolmogorov-Smirnov test (Zar 1984).

A standardized Morisita's index (I_d ; Krebs 1989) was used to describe dispersion patterns in density for each of the three dominant species. This index ranks the distribution of density of a given species from -1 to 1 , with 0 indicating random dispersion, positive numbers indicating clumped dispersion, and negative numbers indicating uniform dispersion. The statistical significance of I_d was determined with methods described in Elliot (1971).

Catch data from fixed stations were used to describe timing of recruitment and changes in density for juvenile rockfishes over time. Frequencies of density grouped by month for each depth stratum were compared graphically versus time for *S. saxicola*, *S. elongatus*, and *S. levis*. Size distributions, including catches from both fixed and random stations, were graphed by depth stratum and month to describe changes over time.

Oceanographic Conditions

Wind data can be used to compute offshore Ekman transport due to wind stress (Bakun et al. 1974). The Pacific Fisheries Environmental Laboratory of NOAA/NMFS provided daily averages of the offshore component of Ekman transport based on wind velocity recorded at 36°N off central California. Sea-surface temperature (SST) data were collected at a buoy station near Monterey Bay (M1: 36°45.25'N, 122°01.10'W) and obtained from the Monterey Bay Aquarium Research Institute.

Sea-surface temperature and offshore Ekman transport were graphically compared with timing and magnitude of recruitment in order to identify possible influences of transport on recruitment. Specifically, comparisons were made to determine whether offshore transport during upwelling and onshore transport during periods of relaxed upwelling might be related to rockfish recruitment in nearshore habitats. Distribution of birthdates estimated from ages of fish at the time of collection can define periods of successful parturition of surviving juveniles. Oceanographic data were graphically compared to birthdate distributions to identify possible influences of ocean condition on survival of recruits.

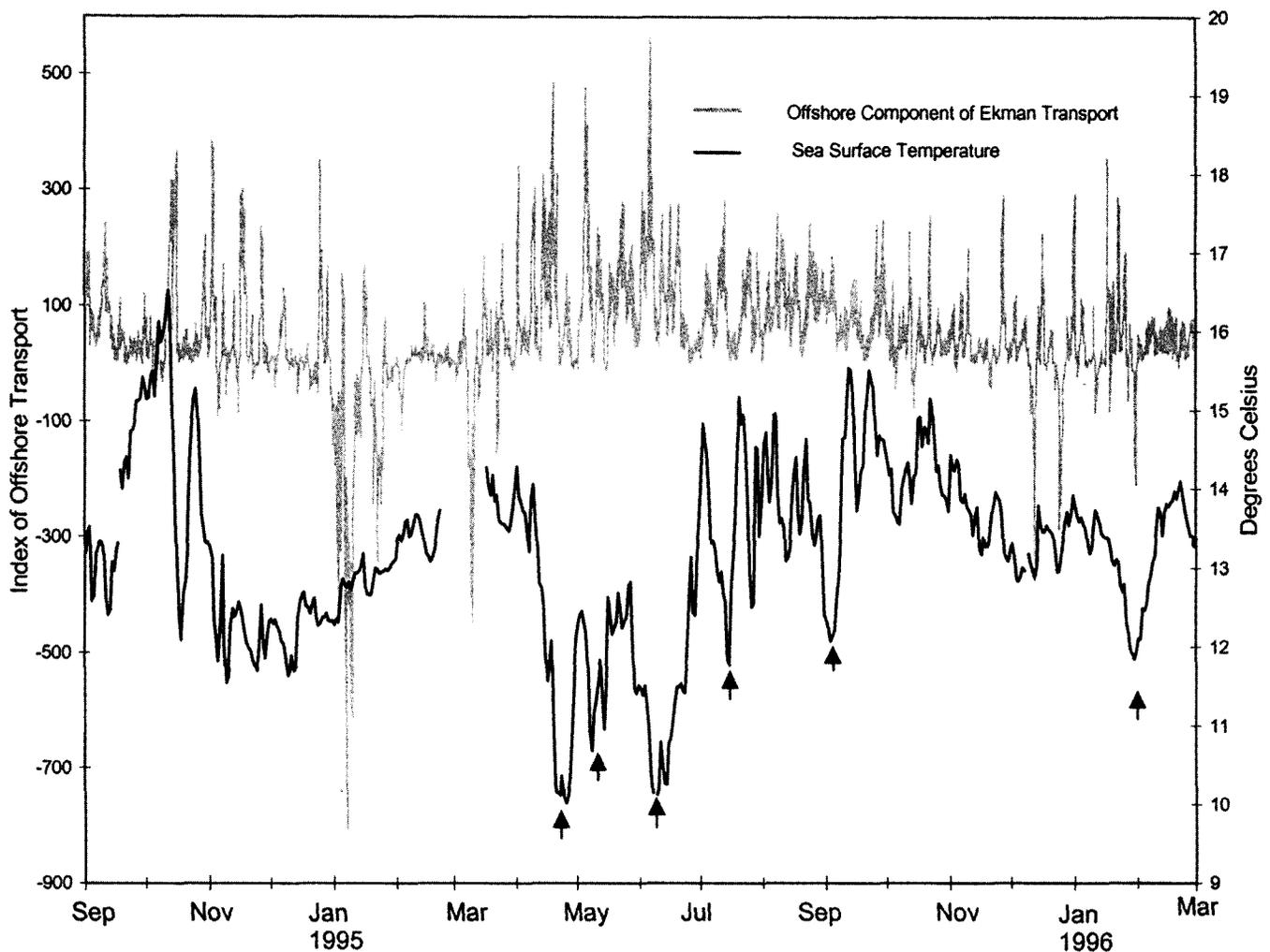


Figure 2. Upwelling off central California from September 1994 through February 1996, as represented by daily averages of sea-surface temperature and offshore component of Ekman transport. Arrows indicate distinct periods of upwelling. Data were obtained from the Monterey Bay Aquarium Institute (M1 buoy) and the Pacific Fisheries Environmental Laboratory of NOAA/NMFS.

RESULTS

Oceanographic Conditions

Upwelling, as represented by high offshore transport and low SST, occurred at intervals between April and September 1995 off central California (fig. 2). SST rapidly dropped from approximately 14°C in March 1995 to 10° at the end of April, indicating the onset of upwelling. SST generally increased through July (with a peak of 14.3°) as summer progressed, but suddenly dropped to 11.8° in mid-July and again in the beginning of September. These periods of relatively low SST generally were associated with increased offshore transport and can be characterized as upwelling.

Temperatures peaked in mid-September and generally remained above 14°C through October. At the same time, offshore transport declined, and periods of onshore transport were evident (negative indices in fig. 2). Another drop in SST occurred at the end of January.

Species Composition and Spatial Distribution

A total of 4,193 fishes from fifteen species of rockfishes were caught in 197 tows completed during 42 cruises (table 1). Three species—*Sebastes elongatus*, *S. saxicola*, and *S. levis*—accounted for over 90% of the total rockfish catch. Each remaining rockfish species accounted for less than 5% of the total catch of rockfish.

The densities of all three dominant species had clumped distributions, with low catches in the shallow depth stratum (table 2). Density of *S. elongatus* (range = 0–144 fish/ha; fig. 3A) and of *S. saxicola* (0–90 fish/ha; fig. 3B) differed significantly among the three depth strata ($p = 0.045$ and 0.001 , respectively). No significant ($p > 0.05$) differences were found in *post hoc* pairwise comparisons of density among the three depth strata for either species. Density of *S. levis* (0–24 fish/ha) was much lower than that of the other two species (fig. 3C), and did not differ among depth strata.

TABLE 1
**Abundance and Length of Juvenile Rockfishes Caught with an Otter Trawl
 on Soft Benthic Habitat in Monterey Bay, California, March 1995–February 1996**

Species	Common name	Abundance		Standard length (mm)	
		Total	% of total	Range	Mean ± SE
<i>Sebastes elongatus</i>	Greenstripe rockfish	1,810	43.2	30–85	41.2 ± 1.0
<i>S. saxicola</i>	Stripetail rockfish	1,736	41.4	32–116	65.8 ± 1.6
<i>S. levis</i>	Cowcod	289	6.9	49–104	66.3 ± 3.9
<i>S. goodei</i>	Chilipepper	182	4.3	65–152	92.5 ± 6.9
<i>S. semicinctus</i>	Halfbanded rockfish	83	2.0	50–140	85.1 ± 9.3
<i>S. crameri</i>	Darkblotched rockfish	37	0.9	48–139	70.2 ± 11.5
<i>S. diploproa</i>	Splitnose rockfish	31	0.7	44–78	57.3 ± 10.3
<i>S. wilsoni</i>	Pygmy rockfish	8	0.2	40–95	57.0 ± 20.2
<i>S. paucispinus</i>	Bocaccio	6	0.1	85–111	94.5 ± 38.6
<i>S. miniatus</i>	Vermilion rockfish	4	0.1	85–102	92.0 ± 46.0
<i>S. hopkinsi</i>	Squarespot rockfish	3	0.1	43–108	85.0 ± 49.1
<i>S. pinniger</i>	Canary rockfish	1	*	94	—
<i>S. jordani</i>	Shortbelly rockfish	1	*	84	—
<i>S. eos</i>	Pink rockfish	1	*	22	—
<i>S. entomelas</i>	Widow rockfish	1	*	92	—
Grand total		4,193	100		

*Less than 0.05% of total rockfish catch.

TABLE 2
**Mean Density and Size by Depth Stratum of *Sebastes elongatus*, *S. saxicola*, and *S. levis*
 Caught over Soft Benthic Habitat in Monterey Bay, California, March 1995–February 1996**

Species	Depth (m)	Density (fish/ha)		Standard length (mm)		
		Mean	S.E.	Mean	S.E.	Range
<i>S. elongatus</i> ($I_d = 0.54^*$; $n = 40$)	40–60	3.5	2.1	40	0.2	32–51
	60–80	23.5	10.6	42	0.1	31–54
	80–100	12.1	2.9	42	0.5	30–85
<i>S. saxicola</i> ($I_d = 0.51^*$; $n = 81$)	40–60	2.6	1.5	50	1.1	32–88
	60–80	10.2	3.7	62	0.5	32–90
	80–100	15.5	3.5	74	0.7	36–116
<i>S. levis</i> ($I_d = 0.54^*$; $n = 77$)	40–60	1.4	1.0	64	1.3	52–76
	60–80	4.1	1.5	65	0.6	49–85
	80–100	0.9	0.3	70	1.2	53–104

I_d is a measure of fish distribution patterns among (n) samples.

* $p < 0.05$.

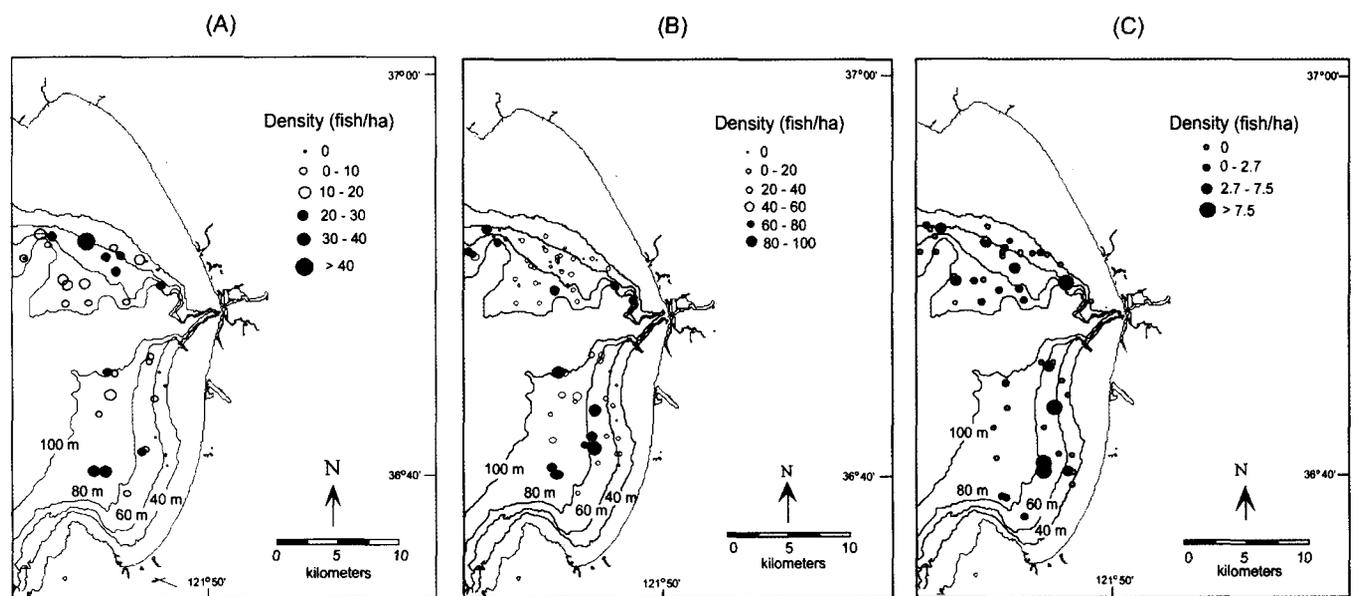


Figure 3. Spatial distribution of *Sebastes elongatus* (A), *S. saxicola* (B), and *S. levis* (C) caught over soft benthic habitat in Monterey Bay, California, between March 1995 and February 1996.

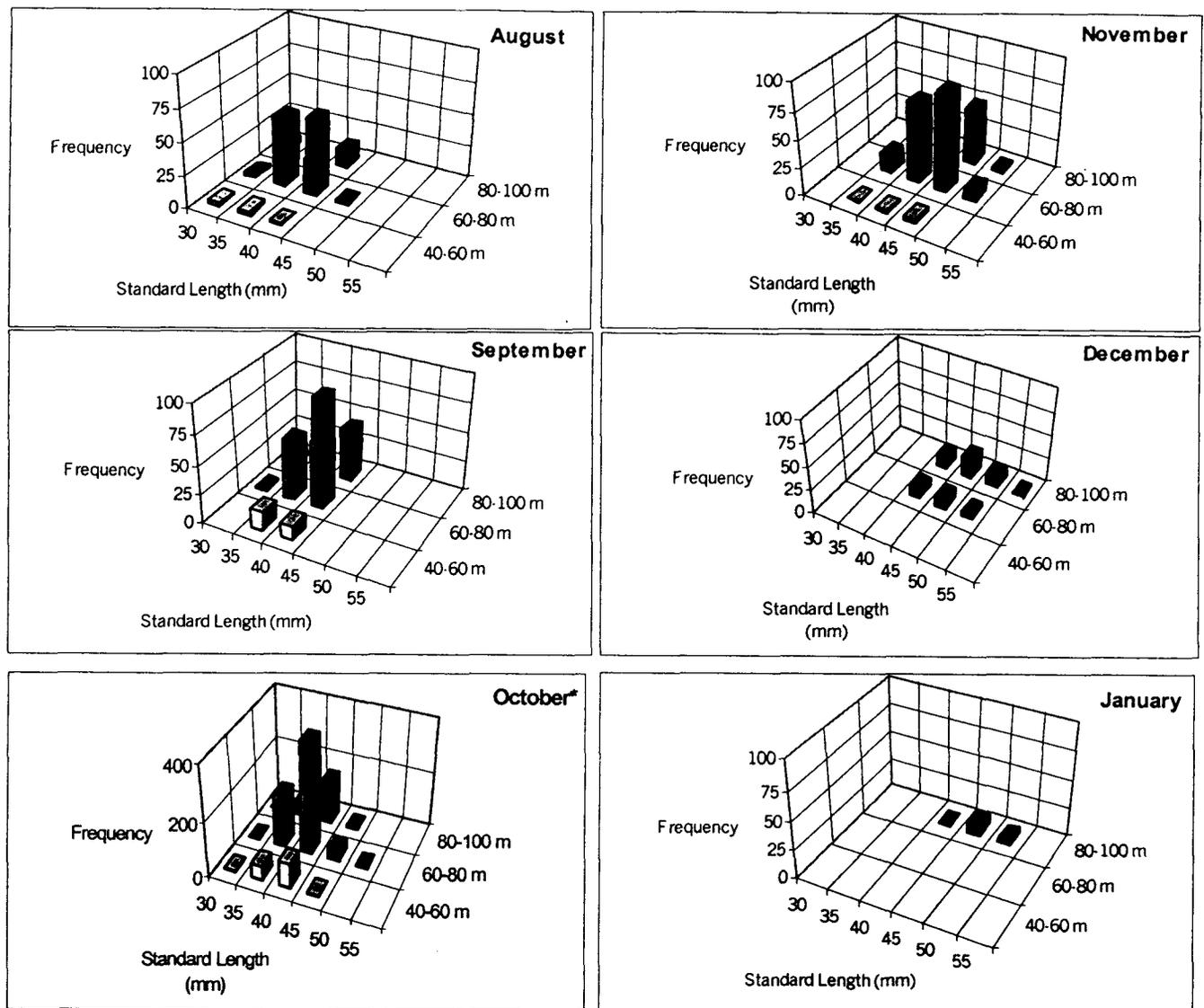


Figure 4. Length frequency of *Sebastes elongatus* by depth stratum (40–60 m, 60–80 m, 80–100 m) by month. Fish were caught at random and fixed stations over soft benthic habitat in Monterey Bay, California. Each depth range was sampled at least monthly between March 1995 and February 1996. (* Note difference in scale for October.)

Size of all three dominant species differed significantly among depth strata ($p < 0.05$; table 2). Only one sample of *S. elongatus* with a mean length >50 mm was collected (in December) in 100 m depth (fig. 4). All samples of the largest *S. saxicola* (mean >90 mm; fig. 5) came from a depth of 100 m. All samples of the largest *S. levis* (mean >80 mm; fig. 6) came from depths >60 m.

Temporal Distribution

In all depth strata, *S. elongatus* first occurred at fixed stations on 23 August, following a long period of high SST that corresponded with a period of relaxation of upwelling (fig. 7). *Sebastes elongatus* were caught only at the deep stations in December and January; none were caught in February. *Sebastes saxicola* was first caught at

deep stations in April, but did not appear at the shallow stations until June. They were still present through February. Relatively large numbers of *S. levis* occurred in early August. They were not collected at the deep stations until September, but were still present at relatively high density through February.

Mean density of all three species was generally highest at the deep stations and lowest at the shallowest depth (fig. 7). All three species increased in abundance simultaneously, with peak density in September and October. This corresponded to a period of relatively high SST, relaxed upwelling, and decreased offshore transport, with periods of moderate onshore transport (fig. 2). Density of all three species declined in November and early December during a period of heavy winter storm ac-

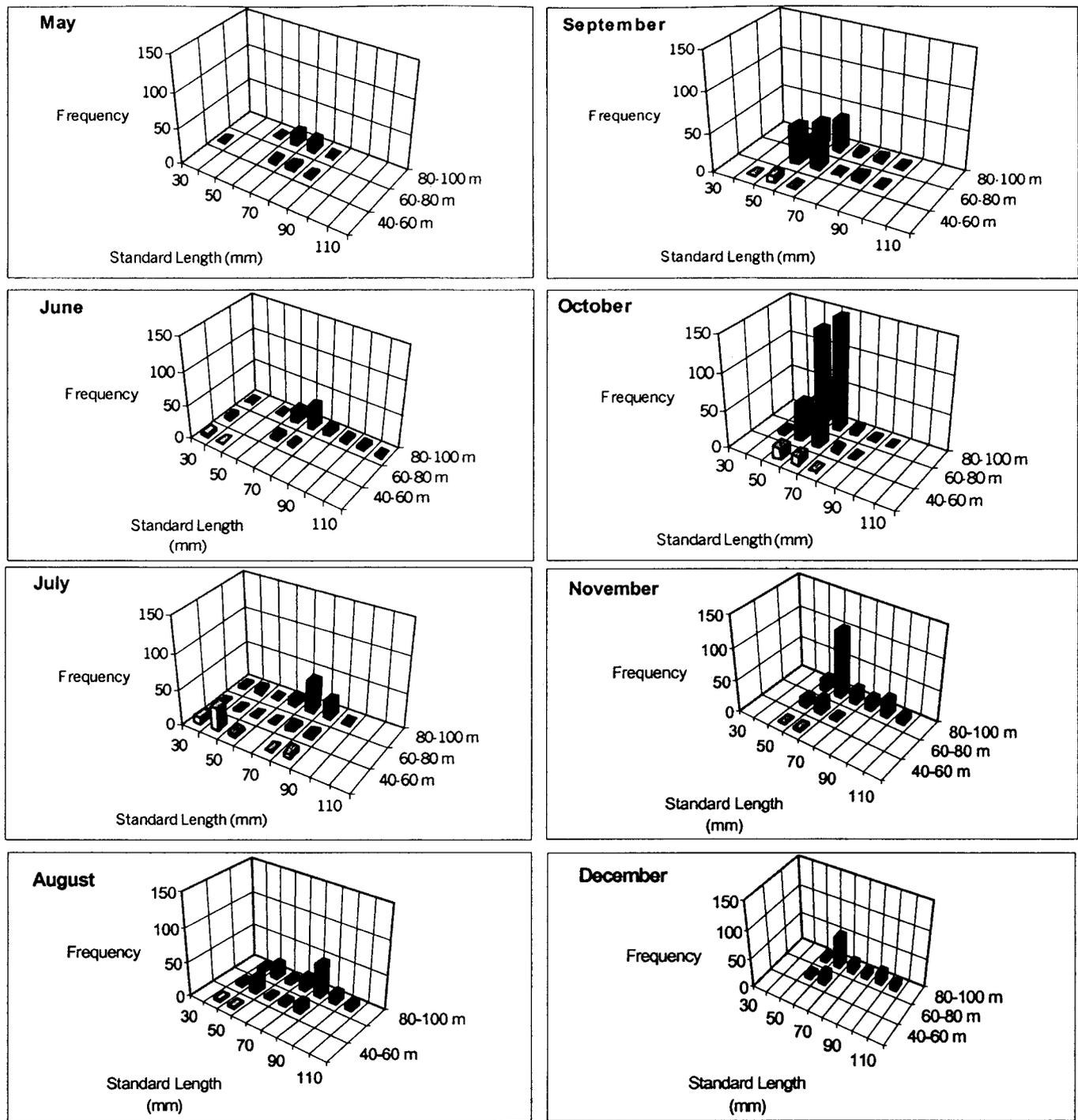


Figure 5. Length frequency of *Sebastes saxicola* by depth stratum (40-60 m, 60-80 m, 80-100 m) by month. Fish were caught at random and fixed stations over soft benthic habitat in Monterey Bay, California. Each depth range was sampled at least monthly between March 1995 and February 1996. *Sebastes saxicola* were caught during each month sampled, but only results from May through December 1995 are shown here.

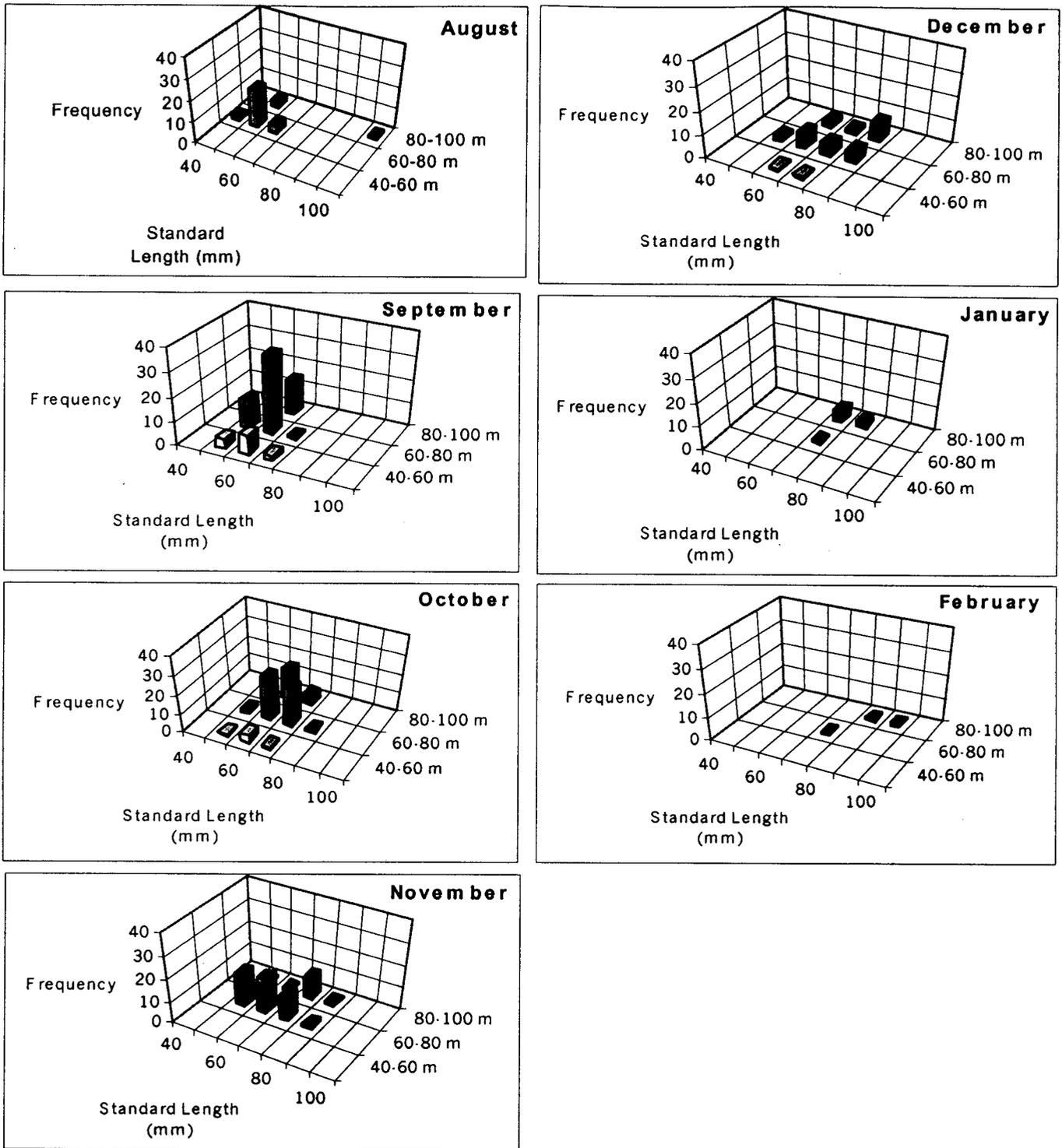


Figure 6. Length frequency of *Sebastes levis* by depth stratum (40-60 m, 60-80 m, 80-100 m) by month. Fish were caught at random and fixed stations over soft benthic habitat in Monterey Bay, California. Each depth range was sampled at least monthly between March 1995 and February 1996. *Sebastes levis* were caught each month between June 1995 and February 1996, but a total of only 3 individuals was caught in June and July.

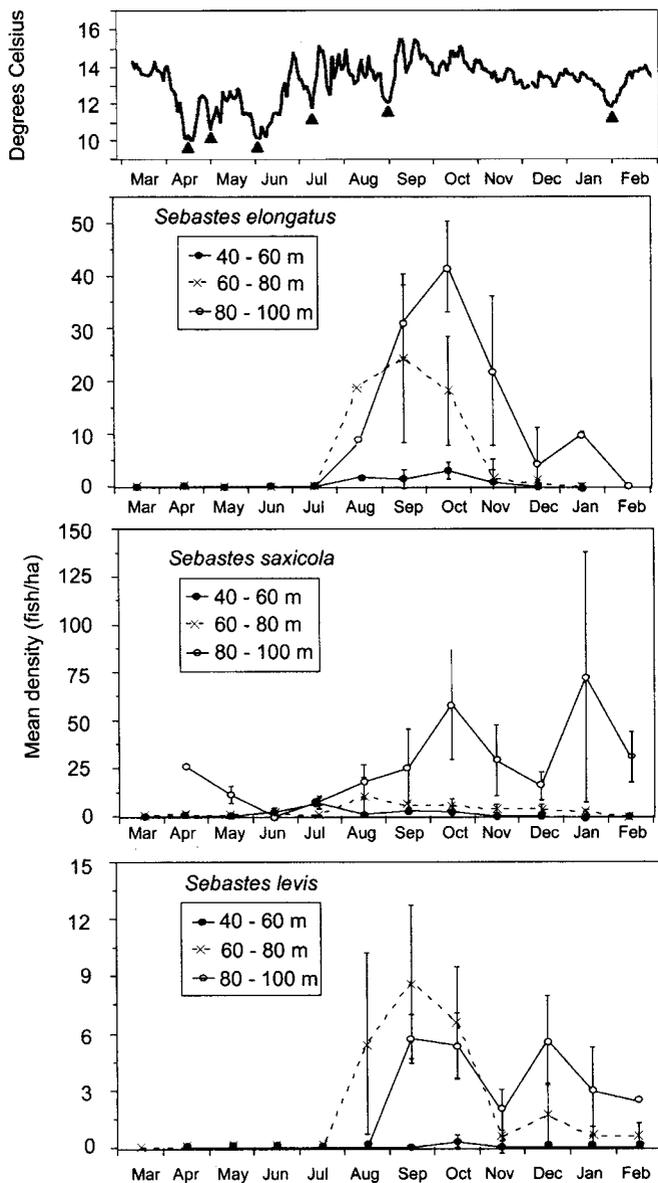


Figure 7. Sea-surface temperature and mean density (fish/ha) of juvenile *Sebastes elongatus* ($n = 634$), *S. saxicola* ($n = 897$), and *S. levis* ($n = 148$) at fixed stations by month. Two to five tows were completed per depth stratum per month. Error bars are one standard error. Arrows in sea-surface temperature denote distinct periods of upwelling. (Note difference in scale among graphs.)

tivity, then increased again in late December and January. This second peak also corresponded to a period of relatively high SST, relaxed upwelling, and increased on-shore transport, with two major periods of onshore transport.

For all three species, size (i.e., modal, minimum, and maximum SL) increased steadily from recruitment to the end of our survey. *Sebastes elongatus* increased in size from August (mean = 38 ± 0.2 mm) to January (mean = 48 ± 0.6 mm; fig. 4). A first cohort of *S. saxicola* (50–80 mm SL) was collected from April through May (fig. 5).

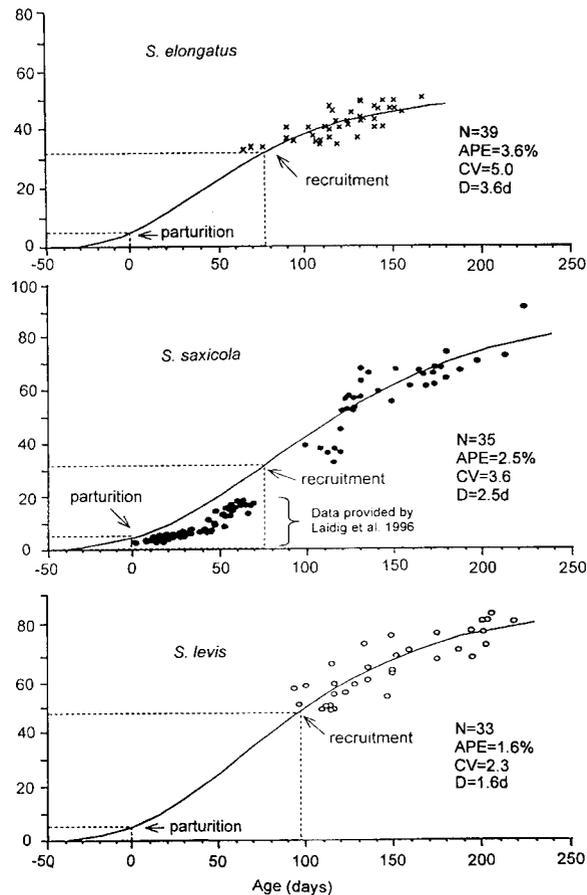


Figure 8. Predicted Gompertz growth functions and size-at-age data for benthic juvenile *Sebastes elongatus*: $L_t = 4.5 \times e^{3.81} [1 - e^{(-0.011t)}]$; *S. saxicola*: $L_t = 5.0 \times e^{2.84} [1 - e^{(-0.016t)}]$; and *S. levis*: $L_t = 5.0 \times e^{2.31} [1 - e^{(-0.021t)}]$. Specimens were caught over soft benthic habitat between 40 and 100 m in Monterey Bay, California, from March 1995 through February 1996. Ages were estimated from daily growth increments of the sagittal otoliths. Sample size, average percent error (APE), coefficient of variation (CV), and index of precision (D) of age estimates are provided for each species.

This cohort increased in catch and size through August and was gone by November. In mid-June, during a period of intense upwelling, a second cohort of small fish (30–40 mm SL) was caught. Density of the second cohort peaked in October. This cohort increased to 70 mm SL and was still present in samples through January. Size of *S. levis* increased from August (mean = 56 ± 0.6 mm) to January and February (mean = 79.9 ± 1.8 mm; fig. 6).

Growth

Growth rates were different among each of the three species (fig. 8). Growth of *S. elongatus* after recruitment, as determined by linear regression, was estimated to be 0.17 mm/day ($r^2 = 0.68$, MSE = 8.35). The growth rate of the second cohort of *S. saxicola* was estimated to be 0.32 mm/d ($r^2 = 0.65$, MSE = 47.35). Estimated growth rate of juvenile *S. levis* was 0.25 mm/day ($r^2 = 0.76$, MSE = 30.71).

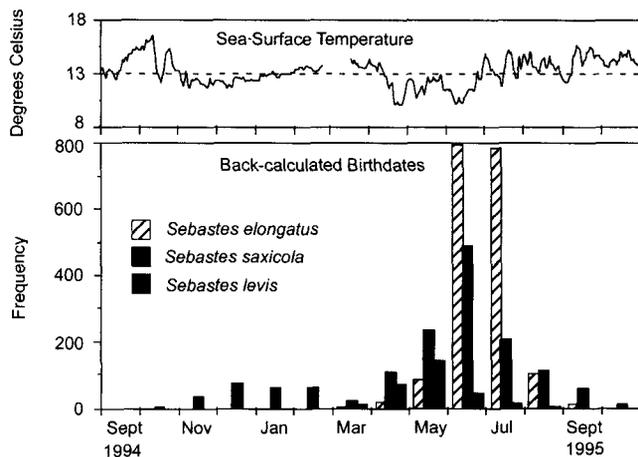


Figure 9. Timing of back-calculated birthdates for *Sebastes elongatus*, *S. saxicola*, and *S. levis* in relation to sea-surface temperature. Fish were caught over soft benthic habitat in Monterey Bay, California, between March 1995 and February 1996.

From the Gompertz growth curves for all three species, including both the data from this study and the larval data from Laidig et al. (1996) for *S. saxicola*, parturition was estimated to occur approximately 30–35 days after fertilization (fig. 8). On the basis of the smallest individuals caught, the initial age at recruitment was approximately 60 days following parturition for *S. elongatus*, 80 days for *S. saxicola*, and 100 days for *S. levis*. The Gompertz model predicted age at recruitment to be 75, 75, and 97 days, respectively.

Birthdate Distributions

Sebastes elongatus birthdates ranged from March through September (fig. 9). However, 98% of the birthdates were between May and August, with a peak in late June and early July. *S. saxicola* birthdates ranged from September 1994 to October 1995, with two peaks in frequency from December through February 1994 and in June 1995. Back-calculated birthdates for *S. levis* ranged from February to August 1995, with a peak in May. For all three species, peaks in back-calculated birthdates corresponded to periods of low SST (fig. 9).

DISCUSSION

Species Composition and Spatial Distribution

Several researchers have examined the recruitment of juvenile rockfish in complex rock habitats along central California. Nearshore fish communities in shallow (generally <25 m water depth) kelp beds and other rocky areas have been the focus of extensive surveys by the California Department of Fish and Game (CDFG) along the central coast from 1987 to 1999 (unpubl. data, D. VenTresca, CDFG, 20 Lower Ragsdale Dr., Monterey, CA 93940). Others have investigated species composi-

tion, development, and food habits of juvenile rockfish recruiting to central California kelp beds (Anderson 1983; Singer 1985; Hoelzer 1988; Carr 1991). Soft sediments in Monterey Bay traditionally have not been sampled for juvenile rockfish, but we collected fifteen species in this habitat at water depths of 40–100 m. Significant recruitment—particularly of *Sebastes elongatus*, *S. saxicola*, and *S. levis*—seems to occur in low-relief sediment on the shelf in Monterey Bay.

Rockfishes develop strong associations with specific substrata throughout different stages of their life (Larson 1980; Carlson and Straty 1981; Richards 1987; Matthews 1990; Carr 1991; Love et al. 1991). The type of habitat varies greatly among species. The adults of all three of the most abundant species in our survey are relatively deep dwelling, but not strictly associated with soft substrata. *Sebastes elongatus* commonly are found from 100–250 m depth, are relatively small (maximum length 43 cm), and associate with mud-cobble substrata near the edges of rocky areas along much of the U.S. West Coast (Percy et al. 1989; Stein et al. 1992; Yoklavich et al. 2000). Adult *S. saxicola* (maximum length 41 cm) are most abundant at 100–200 m (the larger, older adults at deepest depths) and occur predominantly on soft sediments after settlement (Yoklavich et al. 2000). These two relatively small species might not require the shelter and protection provided by high-relief rock habitats. Adult *S. levis* occur most commonly at depths >150 m in high-relief rocky areas, sometimes intermixed with soft mud (Yoklavich et al. 2000). Some of the largest rockfishes (up to 1 m total length), adult *S. levis* are found in rock crevices and under overhangs.

Some of the highest densities for all three species were found at two distinct locations in the southern half of Monterey Bay. Sidescan sonar surveys of the seafloor in southern Monterey Bay identified isolated areas of low-relief granite basement rocks and sedimentary outcrops, bounded by flat mud and sand at about 80–90 m water depth (Greene et al. 1995). Within and around this rocky habitat are linear scarps of cobble and sand patches. Juvenile *S. elongatus* and *S. saxicola* have been observed in these cobble and sand patches from submersibles (pers. observation by M. Yoklavich) and at shallower depths (R. Larson, San Francisco State Univ., 1600 Holloway Ave., San Francisco, CA 94132, pers. comm.). Newly settled *S. levis* have been seen on fine sand and clay sediments as well as over shell mounds and other complex substrata around the base of oil platforms (M. Love, Univ. Calif., Marine Science Institute, Santa Barbara, CA 93106, pers. comm.). It is likely that we sampled within low-lying patches of sand and cobble or along the sand-mud interface around low-relief rock outcrops, resulting in the clumped distributions of these species throughout the bay.

Temporal Distribution

The timing, duration, and magnitude of rockfish recruitment are related to timing of parturition, and to survival and transport of the pelagic stages. These processes are dynamic and result in high interannual and interspecific variation in recruitment (Anderson 1983; Kendall and Lenarz 1987; Carr 1991; Moser and Boehlert 1991). Benthic recruitment of rockfish to shallow (<30 m) nearshore habitats in central California typically occurs between April and August, with peak abundances in summer (Anderson 1983; D. VenTresca, CDFG, 20 Lower Ragsdale Dr., Monterey, CA 93940, unpubl. data). Recruitment of rockfishes to soft benthic habitat in water depths >40 m in Monterey Bay began during June in 1995, and abundance peaked in late summer and early fall. Strong upwelling conditions were still evident during this period, as in earlier months, but there also were periods of relaxed upwelling, with warmer sea-surface temperatures and onshore transport.

The timing and magnitude of recruitment could be influenced by either passive ocean transport or active swimming of pelagic or newly settled juveniles. It is possible that juvenile rockfish reach an ontogenetic stage during which they undergo biological or behavioral changes and begin to move toward shore. Pelagic juveniles are large enough to actively swim toward nearshore environments (Moser and Ahlstrom 1978; Larson et al. 1994) and also may change their position in the water column to minimize the effects of offshore transport and maximize the effects of onshore transport. Pelagic juveniles of many rockfish species, including *S. saxicola*, occur typically between 50 and 100 m, the zone of shoreward flow in an upwelling cell (Lenarz et al. 1991).

The dependence of recruitment on onshore transport was not clear for each of the dominant species. Although the highest recruitment of *S. saxicola* occurred during relaxed upwelling, a few small individuals started to appear in mid-June following a period of distinct upwelling. Similar appearances of larger pelagic *S. saxicola* in nearshore waters of Monterey Bay during heavy upwelling were reported by Larson et al. (1994). This suggests that the trigger for onshore movement by pelagic juveniles is internal and that larger pelagic juveniles may actively move toward nearshore habitats, possibly by regulating their vertical distribution in the water column, even in the presence of offshore advection of the Ekman layer during upwelling. Passive transport by onshore currents would work in concert with these active efforts, resulting in high recruitment during periods of both passive and active transport (Anderson 1983; Carr 1991; D. VenTresca, CDFG, 20 Lower Ragsdale Dr., Monterey, CA 93940, unpubl. data). Peak recruitment of all three species between August and September during this study could have been a result of active transport triggered by

some internal biological signal coupled with oceanographic conditions favorable to onshore transport.

Juveniles of some species of rockfish may take several weeks to a year to reach benthic habitats (Ahlstrom 1961; Boehlert 1977) or may remain in midwater before settling even after they have reached nearshore habitats (Larson et al. 1994). The smallest *S. saxicola* collected during our study was 32 mm, with the majority between 45 and 60 mm. Because of the mesh size of our net, we assume that the smallest benthic fishes were being sampled. Anderson (1983) observed benthic juveniles between 27 and 53 mm in length as early as April on soft sediment at the outer edges of kelp beds in Monterey Bay. Pelagic juveniles caught off central California in midwater trawls during 1984–95 were mostly between 20 and 40 mm, but a few were as large as 52 mm (R. Larson, San Francisco State Univ., 1600 Holloway Ave., San Francisco, CA 94132, pers. comm.). These pelagic juveniles may take some time to reach benthic habitats, but the overlap in size between pelagic and benthic juveniles suggests that they do not settle into intermediate habitats before recruiting to the area sampled in our study.

Pelagic juveniles of *S. levis* are not abundant in samples collected by midwater trawls in May and June off central California: only 30 individuals (SL = 15–58 mm) were caught from 1988 to 1996 (Echeverria et al. 1990). In our study, *S. levis* began recruiting to soft sediments at approximately 50–60 mm in length. The overlap in pelagic and benthic juvenile sizes suggests that *S. levis* does not settle in an intermediate habitat before recruiting to the soft sediments surveyed in this study.

Once juveniles of *S. elongatus*, *S. saxicola*, and *S. levis* recruited to the seafloor, the time they were present in the study area varied. *Sebastes elongatus* recruited at a small size, and remained in the area for approximately three months, with abundances declining sharply for fishes over 50 mm in length. The few specimens that were over 50 mm were caught along the edge of the submarine canyon. *Sebastes saxicola* and *S. levis* recruited at larger sizes, used the area until reaching a much larger size and for a longer time, and attained larger sizes than *S. elongatus* on this habitat. Juveniles of all three species underwent ontogenetic movements to deeper waters, with density and size of fishes increasing with depth, during the course of this study.

Movement to deeper waters could be triggered by a number of physical or biological factors, including temperature, size, age, food conditions, and photoperiod (Boehlert 1981; Boehlert and Yoklavich 1983; Halderson and Richards 1987). In this study, declining density corresponded to a period of increased winter storms in November and early December. When wind and swell were high, fewer numbers of all fishes, not just rockfishes,

were caught in the trawl, suggesting lower efficiency of sampling gear or lower availability of the fish. After storms, density increased, but only in the deep stratum.

Growth

Daily growth increments in sagittal otoliths of *S. elongatus*, *S. saxicola*, and *S. levis* were not directly validated in this study. However, they have been validated for a number of fishes (Brothers et al. 1976; Butler 1989; Stevenson and Campana 1992), including juvenile black rockfish (*S. melanops*) held in the laboratory (Yoklavich and Boehlert 1987). As is the case for several species of rockfishes (Penney and Evans 1985; Laidig et al. 1991; Ralston et al. 1996), a distinct growth increment formed at extrusion. For all analyses of growth and birthdate distributions of *S. elongatus*, *S. saxicola*, and *S. levis*, growth increments were assumed to be daily.

Growth rates of most benthic rockfish juveniles range from 0.20 to 0.31 mm/d (Carlson and Haight 1976; Matthews 1990; Love et al. 1991); higher growth rates have been estimated for *S. jordani* (0.59 mm/d) and *S. paucispinis* (0.72 mm/d; Woodbury and Ralston 1991). During our study, mean growth rates ranged from 0.17 mm/d for *S. elongatus* to 0.32 mm/d for *S. saxicola*.

Birthdate Distributions

Birthdate distributions back-calculated from daily growth increments have been used to evaluate yearly survival of juvenile rockfish (Woodbury and Ralston 1991; Yoklavich et al. 1996). Depending on the time of sampling, birthdate distributions back-calculated from juveniles are often skewed toward newer recruits, because older fish have been subject to more age-specific mortality (Yoklavich et al. 1996). Distributions can be adjusted if size-specific rates of mortality during larval and pelagic juvenile stages can be estimated. For this study, the mortality rates are unknown. Once fish have settled they are subject to a substantially lower rate of mortality than at earlier stages (Campana and Jones 1992); therefore, correction for mortality that has occurred after settlement should not be necessary.

The peak in birthdates for all three dominant species corresponded to a pronounced drop in SST and increase in offshore transport, which occurred during summer 1995. For *S. elongatus* this period matches the narrow range of timing of parturition (Echeverria 1987). This supports our interpretation of daily increments in the otoliths. Also, because birthdates for *S. elongatus* were similar to expected months of parturition, the timing of recruitment might be typical of other years.

For *S. saxicola* a small peak in the distribution of back-calculated birthdates matches the peak months of parturition (November–March; Echeverria 1987). However, a much larger peak occurred between April and August,

completely outside the predicted range. All *S. levis* birthdates fell beyond the predicted dates for parturition. Moser and Boehlert (1991) also reported *S. levis* larvae as late as July in one of five CalCOFI sampling years between San Francisco and Baja California. This timing of parturition for surviving benthic rockfish is most likely a result of higher survival of those individuals born between April and August. Alternately, if growth increments were not produced on a daily basis, individuals would be older than estimated, and birthdates would fall within predicted dates. However, there is no evidence to suggest that growth increments in rockfish otoliths are not daily.

Juvenile rockfish spawned late in the season, after the onset of upwelling, had the highest survival rate. During the end of 1994 and beginning of 1995, temperatures in the California Current were anomalously high, with conditions characteristic of an El Niño year (Hayward et al. 1996). There is successful early parturition for rockfishes during years with normal upwelling intensity (Woodbury and Ralston 1991). During years with reduced or delayed upwelling, successful parturition occurs later in the season; these are years when cumulative survival is poor (Woodbury and Ralston 1991).

Highest survival of *S. mystinus* (blue rockfish) and *S. flavidus* (yellowtail rockfish) occurred when SST and upwelling were at intermediate levels, with low survival during years of extreme temperatures (Ralston and Howard 1995). During a two-year El Niño event, only larvae released late in the year were represented in birthdate distributions of juveniles of *S. jordani* (Yoklavich et al. 1996). The high temperatures early in the 1994–95 parturition season, coupled with late successful parturition as predicted from the birthdate distributions, match findings of these previous studies. Larvae born after the transition to upwelling experienced lower mortality rates and higher survival, possibly because of increased food, growth, and offshore transport away from nearshore predators.

Another explanation for higher abundance of those born late in the season is that juveniles from earlier periods of parturition either survived to the stage of settlement and perished after settlement, or all settled outside of Monterey Bay. In March 1995, unusual flood conditions in the Salinas Valley affected nearshore conditions in the bay. The Salinas and Pajaro Rivers, which typically have low flows, poured large amounts of water, silt, and debris into Monterey Bay. Waters throughout Monterey Bay were brown and turbid. Unusual amounts of silt, mud, and debris were present in our samples, and fewer fish of all species were caught during this time. These conditions could have been unsuitable for juvenile rockfish survival. Assuming juveniles born earlier in the year settle at the same size and age as those that set-

tle later in the year, juveniles born during peak periods of spawning for *S. saxicola* and *S. levis* would have been recruiting to benthic habitats during these conditions of poor water quality. This could explain survival of only those individuals born later in the season, when conditions for recruitment had improved.

CONCLUSIONS

Our study suggests that soft benthic sediments provide important habitat for recruitment of some relatively deep-dwelling rockfishes. This habitat, along with near-shore rock outcrops and kelp forests, could be considered essential fish habitat—nursery areas that are particularly important to the survival of rockfish populations. Furthermore, oceanographic conditions could influence both the timing of juvenile recruitment and the survival of recruits during larval and pelagic juvenile stages.

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ESTIMATIONS OF CATCHABILITY-AT-LENGTH FOR THE JUMBO SQUID (*DOSIDICUS GIGAS*) FISHERY IN THE GULF OF CALIFORNIA, MEXICO

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ABSTRACT

In this paper, we used the deterministic model of catchability (DMC) for the jumbo squid (*Dosidicus gigas*) fishery. The DMC assumes that catchability depends on length as well as on squid behavior. We analyzed the variation in the catchability coefficient (q) of *D. gigas* from the Gulf of California, Mexico, based on population length-structured data (mantle length = ML) expressed as CPUE from 5 November 1995 to 16 November 1996. The results showed two patterns: (1) low catchability for 19–27 cm, 43–49 cm, and 57–63 cm of ML; and (2) high catchability for 29–33 cm, 53–57 cm, and 65–71 cm of ML. This variation in catchability-at-length was explained by an overlap of two cohorts dominant in a recruitment period in May 1996. The catchability coefficient showed an overlap of cohorts. We found three peaks of catchability with approximately the same value ($q \approx 0.7 \times 10^{-3}$). These high values of catchability for 29–33 cm, 53–57 cm, and 65–71 cm of ML showed that these intervals have the same vulnerability. Although we recognize a dominant cohort in the fishery, the catchability estimates suggest the presence of three cohorts, since catchability is similar among intervals.

INTRODUCTION

Managers commonly use catch-per-unit-of-effort (CPUE) methods for estimating population size and catchability coefficients in squid fisheries, because these parameters are key in the exploitation. The objective for squid fisheries is to establish a management strategy that involves a limited fishing effort (licenses) and an estimation of the proportional escapement. Stock assessment for the jumbo squid (*Dosidicus gigas*) fishery has used models reviewed by Rosenberg et al. (1990) and Beddington et al. (1990), particularly the depletion model of Delury and the multifleet model (Morales-Bojórquez

et al. 1997; Morales-Bojórquez, Hernández-Herrera et al. 2001).

In the Gulf of California, survey data have made it possible to tune a biomass model that includes the growth and decay of a single cohort (Alverson and Carney 1975; Hernández-Herrera et al. 1998). For jumbo squid, CPUE has been used as an index of abundance in the fishery, assuming a constant catchability during the fishing season (Morales-Bojórquez et al. 1997; Nevárez-Martínez and Morales-Bojórquez 1997; Hernández-Herrera et al. 1998). This assumption is a risk factor in the stock assessment and management of the fishery, especially if CPUE data are measured with error (Hilborn and Walters 1992).

The stock assessment for the jumbo squid fishery uses a deterministic model assuming a CPUE index without error (Nevárez-Martínez and Morales-Bojórquez 1997). The management strategy has been based on the estimation of proportional escapement (Rosenberg et al. 1990; Nevárez-Martínez and Morales-Bojórquez 1997; Morales-Bojórquez, Hernández-Herrera et al. 2001). The control mechanism is the limiting of the number of licenses before the start of the fishing season (Basson and Beddington 1993; Hernández-Herrera et al. 1998). In this management approach, recruitment and the constant catchability coefficient are the main sources of uncertainty and risk.

Basson and Beddington (1993) have analyzed the variation in recruitment in detail. However, analysis of catchability in one fishing season using time-series CPUE is usually made under the assumption that catchability remains constant (Atran and Loesch 1995; Tanaka 1997). Some mechanisms that may cause variability in catchability are sensory capabilities and behavioral response of the target species (Penn 1975); environmental factors (Hill 1985); stock area and the relative distribution of fish and fishing (Winters and Wheeler 1985); stock abundance (MacCall 1976; Martínez-Aguilar et al. 1997);

density-dependent effects and differences between fleets (Arreguín-Sánchez 1996; Arreguín-Sánchez and Pitcher 1999); and schooling behavior (Ye and Mohammed 1999).

The variation in catchability is the greatest source of error in stock assessment methods based on CPUE data (Ricker 1975; Hilborn and Walters 1992; Atran and Loesch 1995; Ye and Mohammed 1999). Gould et al. (1997) and Gould and Pollock (1997) have evaluated the error of catch and effort data, analyzing changes in the catchability coefficient and recruitment using catch-effort regression methods. They show that, in most cases, errors in catch and effort data have inflated the parameter estimates.

In squid fisheries, changes in the catchability coefficient between seasons can be analyzed (Brodziak and Rosenberg 1993). However, variations in catchability-at-length for one fishing season remain unmeasured (Basson et al. 1996; Morales-Bojórquez et al., in press). The last problem can be solved with an analysis of variation in catchability-at-length, which can give some information about stock behavior and efficiency of fishing, and concomitantly improve the quantities used for management, such as changes in fishing mortality during the fishing season. We assumed that catchability in the *D. gigas* fishery is variable. Under this condition, the risks in management decisions and harvest strategies decrease because catchability is a parameter relating fishing effort to fishing mortality and stock abundance (Arreguín-Sánchez 1996; Arreguín-Sánchez and Pitcher 1999). For this study, we analyzed the variation in the catchability coefficient of *D. gigas* on the basis of population length-structured data expressed as CPUE.

METHODS

Weekly catch (kg) and effort (number of fishing nights of landed catch) data were obtained from the Subdelegación de Pesca de Guaymas, Sonora, Mexico (fig. 1). This information represented catch records for a fleet of shrimp trawlers adapted with hand jigs as fishing gear for squid. We analyzed the CPUE data by considering the fishing season, t (1 year, fig. 2), from 5 November 1995 to 16 November 1996, and the fishing season, $t + 1$ (1 year, fig. 3), from 17 November 1996 to 29 November 1997. We selected these times because recruitment of *D. gigas* occurs in May on the fishing ground off Guaymas, Sonora (Hernández-Herrera et al. 1998), so we could observe the effect on catchability when the presence of one new cohort of *D. gigas* supports the fishery throughout the fishing season.

Nevárez-Martínez et al. (2000), Brito-Castillo et al. (2000), and Morales-Bojórquez et al. (in press) showed that during 1995–98 the jumbo squid population was found only in the north of the Gulf of California, mainly off Santa Rosalía and Guaymas (fig. 1). They observed

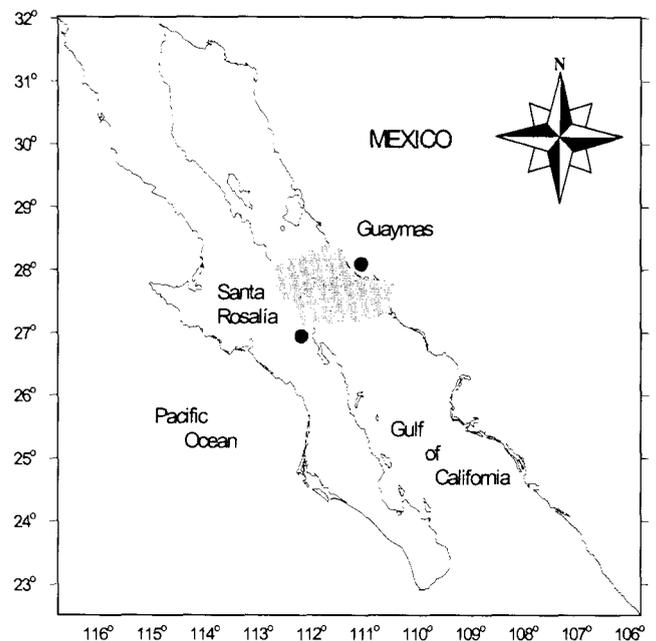


Figure 1. Study area in the Gulf of California, Mexico. Shaded area indicates where catches of *D. gigas* were made. Since 1995 over 85% of the catch has been taken in this area of the Gulf of California.

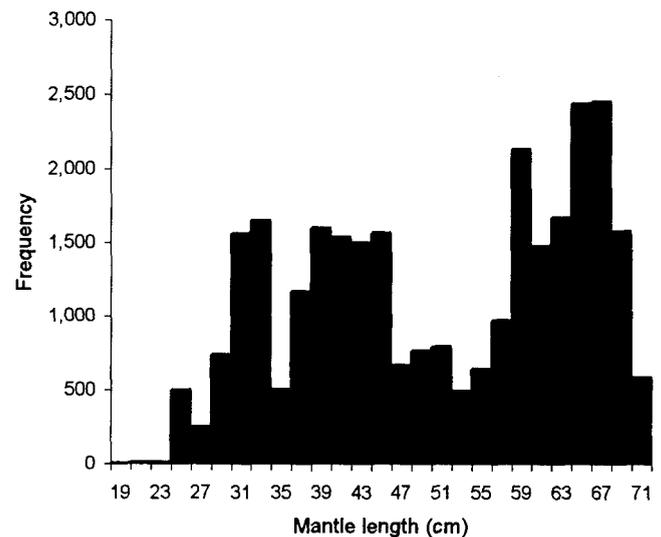


Figure 2. Mantle length distribution for *D. gigas* at time t (from 5 November 1995 to 16 November 1996).

population movement from Santa Rosalía toward Guaymas. During this movement, recruitment took place in May. A stock assessment using survey data from the Gulf of California also confirmed that *D. gigas* was not distributed in the southern Gulf of California (Nevárez-Martínez et al. 2000).

We estimated catchability-at-length by using the deterministic model of catchability (DMC) proposed by Arreguín-Sánchez (1996). The DMC assumes that catchability (q) depends on length as well as on squid behavior

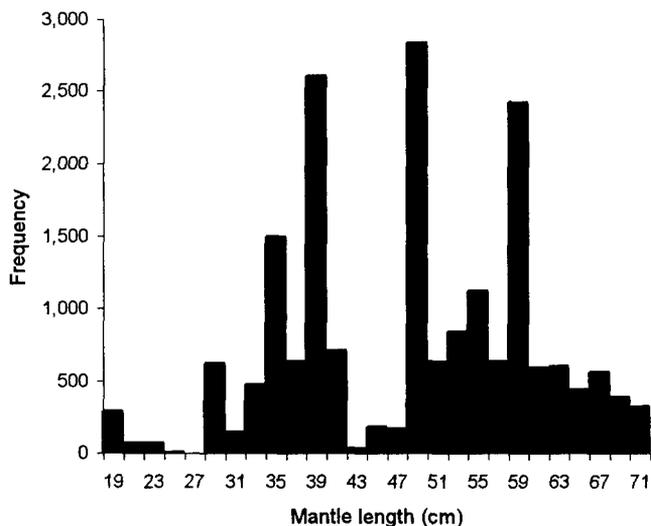


Figure 3. Mantle length distribution for *D. gigas* at time $t+1$ (from 17 November 1996 to 29 November 1997).

(Arreguín-Sánchez and Pitcher 1999). The catchability must be estimated for each length class (l) in a given time (t). According to Arreguín-Sánchez and Pitcher, a convenient method for representing the transformation of one length frequency into another is a transition matrix (Shepherd 1987; Caswell 1988), expressed as $N(l, t+1) = A(l, w)N(l, t)$, where w and l are successive length intervals; $N(l, t)$ is the vector of stock size in numbers at time t (from 5 November 1995 to 16 November 1996); $N(l, t+1)$ is the vector of stock size in numbers at time $t+1$ (from 17 November 1996 to 29 November 1997); and A is the transition matrix that depends on growth and mortality. In both cases, $N(l, t)$ and $N(l, t+1)$ are represented as catch per unit of fishing effort. Shepherd (1987) expressed A as: $A(l, w) = G(l, w)S(w)$, where $G(l, w)$ represents growth in the absence of mortality, and $S(w)$ is the survival matrix and represents the effect of mortality.

Growth probabilities of $G(l, t)$ are defined assuming that individuals are growing following the von Bertalanffy model (VBM), and the probabilities were estimated following Shepherd (1987) as indicated in table 1. Growth parameters of the VBM were taken from Hernández-Herrera et al. (1998), where the growth of individuals of a single cohort off Guaymas, Mexico, is well-documented ($k = 0.8$, $SE = 0.06$, and $L\infty = 87$ cm, $SE = 2.7$ cm).

$S(w)$ is defined as $S(w) = \exp^{-Z(w)t} = \exp^{-[M + F(w)t]}$, where $Z(w)t =$ total mortality for the w th length group at time t ; M is natural mortality (constant), estimated with the Silliman method (Ricker 1975) as $M = 0.101/\text{week}$ (Morales-Bojórquez, Hernández-Herrera et al. 2001); and $F(w)t =$ fishing mortality for the w th length group at time t . $F(w)t$ is defined as $F(w)t = q(u, t)E(t)$, where $q(u, t) =$ catchability for the w th length group at

TABLE 1
 Computations to Estimate Growth Probabilities per Length Class

1. $G(l, w) = 0$	...if...	$L(w+1) < \tilde{L}(l)$
2. $G(l, w) = [(L(w+1) - \tilde{L}(l))/\Delta L]$	...if...	$L(w) < \tilde{L}(l) < L(w+1)$
3. $G(l, w) = 1.0$	...if...	$\tilde{L}(l) < L(w)$ and $L(w+1) < \tilde{L}(l+1)$
4. $G(l, w) = [(\tilde{L}(l+1) - L(w))/\Delta L]$	...if...	$L(w) < \tilde{L}(l+1) < L(w+1)$
5. $G(l, w) = 0$	...if...	$\tilde{L}(l+1) < L(w)$
In the last interval of length		
6. $G(l, w) = 1.0$	...if...	$l = L_{max}$ and $\tilde{L}(l) < L(w)$

Source: Shepherd 1987

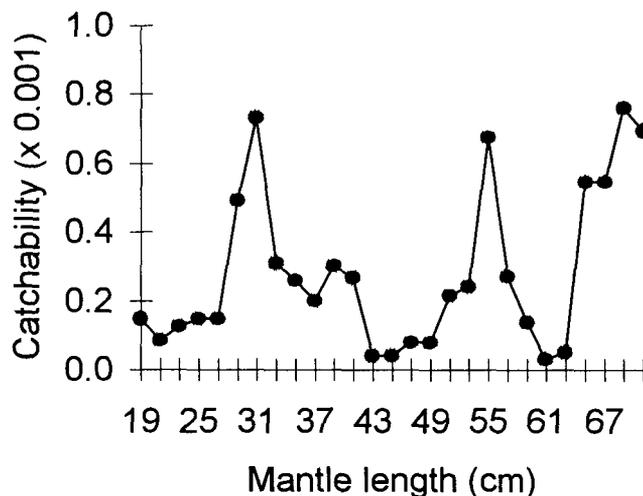


Figure 4. Estimations of the catchability-at-length coefficient.

time t , and $E(t) =$ fishing effort at time t . In this way, the stock size in numbers at time $t+1$ can be estimated as

$$N(l, t+1) = \sum_w G(l, w) \exp^{-[M + q(u, t)E(t)]} N(w, t) \quad (1)$$

Because growth matrix, stock size in numbers at time t and $t+1$, and parameters are known, then $q(u, t)$ can be estimated from equation 1 by a simple least squares algorithm (see Arreguín-Sánchez 1996; Arreguín-Sánchez and Pitcher 1999 for details).

RESULTS

The variation of the catchability coefficient with length for *D. gigas* is shown in figure 4. The average value of catchability along the range of sizes of mantle length was $\bar{q} = 2.8 \times 10^{-4}$ (s.d. = 2.3×10^{-4}), and the range of variation was $3.1 \times 10^{-5} < q < 7.6 \times 10^{-4}$. The standard deviation is high because of the fluctuations in catchability coefficient within a season. Catchability-at-length showed an alternating pattern of low and high values along the range of sizes as follows: (a) low catchability at 19–27 cm, 43–49 cm, and 57–63 cm ML, and (b) high catchability at 29–33 cm, 53–57 cm, and 65–71 cm ML. In this pattern, an increase in catchability is fol-

lowed by a rapid decline. Three peaks in catchability coefficient are observed, at 31 cm, 55 cm, and 69 cm of mantle length. Between peaks were organisms with low catchability between 43–49 and 61–63 cm ML.

DISCUSSION

An alternative method for estimating catchability in the jumbo squid fishery is desirable because in the management strategy the size of the incoming cohort is unknown at the time of licensing and also varies from year to year. The number of licenses that are allocated in accordance with the target escapement is dependent on information about effort patterns and vessel efficiency (estimates of catchability coefficient). It is at the assessment stage during the fishing season that need for a closure can be detected and corrective action taken if required. The need for a closure can be caused by one or both of the following reasons: a low level of recruitment, and changes in the efficiency or operational practices of vessels (catchability; Basson and Beddington 1993).

Low levels of recruitment were estimated in 1998 (Morales-Bojórquez et al., in press) with a Delury model (Rosenberg et al. 1990), but the assessment failed because the model could not be fitted to the data of CPUE and cumulative catch. That is, in some cases the Delury model fit was poor and produced skewed likelihood functions or a curvature of the depletion regression (fishing season 1996–97; Morales-Bojórquez et al. 1997). This trend in the depletion regression is explained by Beddington et al. (1990), assuming that the catchability coefficient is a measure of vessel efficiency, and is constant throughout the fishing season.

Ricker (1975), and Hilborn and Walters (1992) comment that nonconstant catchability is the greatest potential source of error in depletion methods. Often the first few units of catch effort rapidly deplete more vulnerable fish, with accompanying rapid change in CPUE or other abundance indices. After this initial catch, the remaining squid have effectively lower q values, so that q declines progressively as the depletion proceeds. There may even be a large pool of squid with $q = 0$ for some reason, and this pool will not be sampled at all by the depletion process. The general effect of varying catchability among individuals is to bias the estimate of q upward and to bias the estimate of recruitment downward. This effect is likely to be much larger than the upward bias caused by statistical error, so the depletion estimate of recruitment is likely to be too low. Hilborn and Walters (1992) consider underestimates of 30% to 50%. Thus the presence of large numbers of squid with low catchability may be indicated by curvature (flattening) of the depletion regression.

This curvature could be caused by differences in the behavior of the fleet or of squid during the fishing sea-

son. In the jumbo squid fishery, we recognize changes in catchability because interactions between the shrimp and jumbo squid fisheries temporally modify the distribution of the shrimp trawlers. That is, the shrimp fishing season begins in August–September; when yields of shrimp diminish (December; Morales-Bojórquez and López-Martínez 1999; Morales-Bojórquez, López-Martínez et al. 2001), the shrimp trawlers are adapted with hand jigs as fishing gear for squid. During this time the squid stock is distributed near the coast of Guaymas, and squid with mantle lengths between 45 and 70 cm are observed in the landings. The fleet fishes near the coast, exploiting one resident cohort of adults in the fishing ground off Guaymas (Hernández-Herrera et al. 1998).

The exploitation of this cohort was observed from 5 November 1995 to 4 May 1996 (Morales-Bojórquez et al., in press). During this time only adult individuals are available (Hernández-Herrera et al. 1998), which explains low values of q for individuals from 39 to 50 cm ML (low frequency from November 1995 to May 1996), and high values of q for squid between 55 and 71 cm ML that are well represented in the samples (fig. 2). The fluctuations in q for the 55–71 cm ML can be an effect of aggregation of jumbo squid in the fishing ground, because the cohort has only squid with ML >50 cm. Basson et al. (1996) showed that the catchability coefficient can also reflect the spatial density of squid.

In May a new recruitment into the fishery of *D. gigas* is detected (Hernández-Herrera et al. 1998), coinciding with the beginning of the closed season for the shrimp fishery. At this time, the shrimp trawler fleet receives more squid licenses. During this time, there is an overlap of cohorts, dominated by the new cohort. Individuals of 20 cm ML are observed, but the recruitment is of squid with ML of 30 cm. This recruitment explains high q -values in younger individuals (fig. 4). We have no evidence for more cohorts of *D. gigas* in the Gulf of California. Previous authors show that different groups of catchability coefficients indicate two or more cohorts in the fishery (Basson et al. 1996; Agnew et al. 1998). In our study the groups of q showed an overlap of cohorts.

We found three peaks of catchability, and these peaks have approximately the same value ($q \approx 0.7 \times 10^{-3}$). High values of catchability at 29–33 cm, 53–57 cm, and 65–71 cm ML showed that these intervals have the same vulnerability. Although we recognize a dominant cohort in the fishery, the catchability estimates suggest the presence of three cohorts, since the catchability is similar among intervals. However, the first interval indicates that the cohort that has been resident on the fishing ground up to the end of May is being replaced by a new cohort, which will become resident once it has fully recruited.

In the jumbo squid fishery, real-time management (in season) is required, because an annual cohort supports

the harvest, makes up an open access fishery, is highly available in the coastal zone, and has low effort costs. Thus the bias and errors in catchability cannot be omitted. It would be useful to have a supplementary method for assessing cohort size either in the absence of a successful Delury assessment or survey data. If we consider the bias and errors in the management quantities, then the advantage of the DMC method is to explain the changes in catchability as length dependent according to squid fishery behavior. In this way, we can obtain information on current stock size, project final stock biomass and escapement, and identify the type of catchability that is applicable to this fishery in order to improve its exploitation and management.

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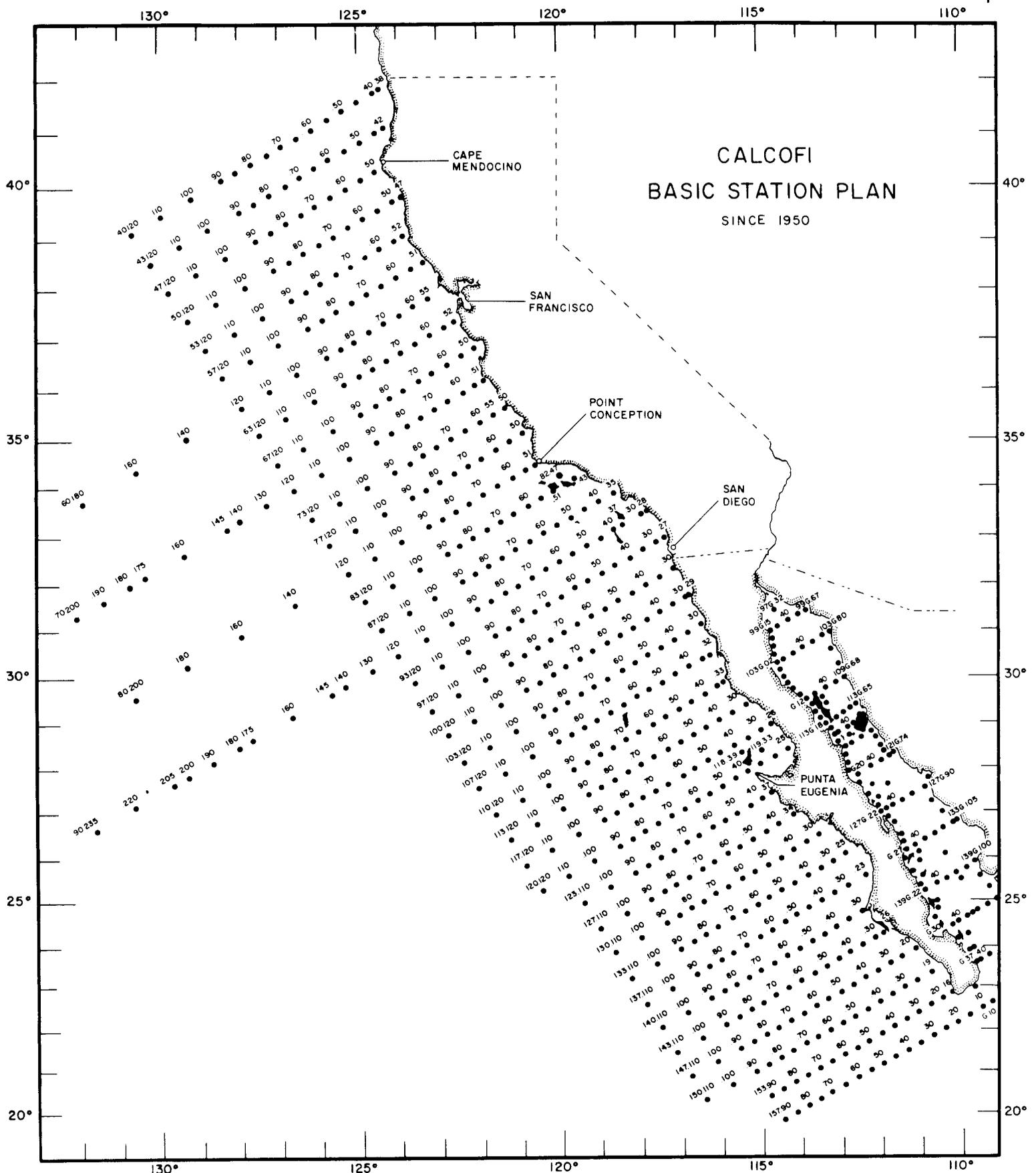
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Each figure must have a *caption*; captions should be typed, **double-spaced**, in numbered sequence on a separate sheet.

Acknowledgments, if included, should be placed at the end of the text and may include funding source.

The *final, accepted manuscript* should be submitted in hard copy and on disk, either as a Microsoft Word document or a WordPerfect document, formatted as described (see "Manuscript"). The disk and hard copy must be **identical**.



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BASIC STATION PLAN
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