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IN MEMORIAM

ANGELES ALVARIÑO
1916–2005

CalCOFI Systematist and Biological Oceanographer Dies

Classically trained Continental Natural Scientist, Dr. Angeles Alvariño, joined the renowned SIO team of zooplankton biogeographers in 1958 to assist in studying the biological oceanography of the great El Niño of 1957–59. This was the first El Niño to be fully described by the California Cooperative Oceanic Fisheries Investigations (CalCOFI) hydrographic and plankton surveys. While continuing her global interest in the systematics of the zooplankton predators, she joined the NMFS Fisheries Oceanography Center team led by Dr. Elbert Ahlstrom, Dr. Reuben Lasker, and Dr. Longhurst in 1970. She redirected her efforts to the applied science of interpreting ichthyoplankton distribution, abundance, and mortality by analysis of the horizontal and vertical distribution of invertebrate planktonic predators in relation to the early life stages of commercially valuable fishes.

Dr. Alvariño's early education was in El Ferrol, Spain, followed by college in Santiago de Compostela and at the University of Madrid. She interrupted teaching and her work at the Spanish Department of Sea Fisheries to continue advanced studies. Her renowned mentors in oceanography were Sir Frederick Russell of the Plymouth Marine Laboratory in 1953 and Mary Sears of Woods Hole Oceanographic Institution in 1956. From 1958 until 1970, Dr. Alvariño was a research scientist in the Marine Life Research Group of Scripps Institution of Oceanography at the University of California San Diego. She joined the newly formed Department of Commerce, National Oceanic and Atmospheric Administration, Fisheries Oceanography Center at La Jolla and remained there for the rest of her career, through 1987.

Dr. Alvariño is the author of about 100 scientific publications. She was among a very few global authorities on the predatory zooplankton, including chaetognaths [arrow worms], the complex colonial siphonophores [Portuguese Man of War, for example], and hydromedusae [jelly fish]. Dr. Alvariño described 22 new species from these groups and also a pelagic octopus. In the early days of collaborative work of NOAA with faculty and students of Hispanic-American University, Angeles Alvariño forged a vital link in imparting scholarly traditions.

Paul E. Smith (Retired)
Ed Brinton

Left: Dr. Angeles Alvariño with colleagues at a Sardine/Anchovy Recruitment Program meeting. (From left Ronald Lynn, Angeles Alvariño, Alex Herman, Robert Owen, Geoffrey Moser, Patricio Bernal, Richard Barber).

Right: Dr. Angeles Alvariño delivering a paper at a CalCOFI Meeting.

Part I

REPORTS, REVIEW, AND PUBLICATIONS

REPORT OF THE CALCOFI COMMITTEE

CALCOFI FIELD SEASON

The 2004 CalCOFI field season was highlighted by four successful quarterly cruises that included additional projects beyond the existing CalCOFI survey structure. As was the case in 2003, the spring survey was conducted aboard multiple vessels enabling more extensive coverage of the Pacific sardine (*Sardinops sagax*) spawning range. In addition, the SWFSC was able to charter the fishing vessel *Frosti* to sample adult sardines within the survey region with guidance from the NOAA ship *David Starr Jordan* and the R/V *New Horizon* from SIO. The F/V *Frosti* completed nineteen surface trawls in which fourteen were positive for adult or juvenile sardine. Aboard the R/V *New Horizon*, CalCOFI began a partnership during the April survey with researchers from the LTER group at SIO. Measurements of trace metals, dissolved and particulate organic carbon, and particulate calcium are now added to the extensive suite of CalCOFI measurements. A new project measuring recorded marine mammal acoustics, led by Dr. John Hildebrand of GRD and MPL at SIO, also began during the spring survey.

Coastal sea surface temperatures (SST) remained seasonally average from the beginning of the year through March of 2004. April displayed positive anomalies of SST in the northern region while the Southern California Bight remained within seasonal averages. In May, positive SST anomalies were observed throughout most of the coastal areas from the Mexican border up to the Gulf of Alaska. These positive SST anomalies persisted through October with the largest anomalies seen in August at approximately +2.5°C. Illustrating the effect of these positive anomalies, the usual Baja California resident, the Humboldt or Jumbo squid (*Dosidicus gigas*), was collected as far north as the Gulf of Alaska.

During the March–April survey, both the R/V *New Horizon* and the NOAA ship *David Starr Jordan* collected very few Pacific sardine eggs in the Southern California Bight. The majority of the sardine eggs were collected north of Point Conception with the bulk of the egg distribution centered on Monterey Bay. While the absolute numbers of Pacific sardine eggs collected were significantly less than those seen in previous years, Northern anchovy eggs were distributed farther offshore and farther north (north of Point Conception) than previous years.

CALCOFI ICHTHYOPLANKTON

The 2004 CalCOFI ichthyoplankton database has been completed and a data report prepared. Interesting trends in the data include continuing declines in larval incidence and abundance of Pacific sardines off southern California (CalCOFI lines 77–93); incidence peaked in 1998 and abundance in 1999, and by 2004 both had declined to their lowest level since 1984. Although the winter and spring surveys indicated increased incidence and abundance off central California (CalCOFI lines 60–73) from 2003–04, it was not enough to offset the decline in the combined areas. Average larval abundance of northern anchovy peaked off southern California in 1987 and subsequently declined substantially, but at an increasingly slower rate in recent years. In 2004 it increased slightly. Preliminary examination of the winter and spring 2005 CalCOFI samples suggests that larval anchovy abundance may be higher again this year, which might be interpreted as the beginning of an anchovy resurgence, although it is too early to know.

PACOOS

Participants of the 2001 CalCOFI Conference recommended the development of a comprehensive observing system for the entire pelagic ecosystem of the California Current, built upon the foundation of the CalCOFI survey program, but expanded to cover the entire system by adding new partners. This was a tough time (2001–02) to begin planning such a project since the existence of CalCOFI surveys was threatened and the GLOBEC plankton-based hydrographic surveys in Oregon and Washington, an important potential partner, were soon to be discontinued. In 2005, however, the system envisioned by the 2001 conferees may soon become a reality under a consortium known as PaCOOS, Pacific Coast Ocean Observing System. The CalCOFI survey program has been stabilized, and the survey lines in Oregon and Washington have been continued under PaCOOS. Central California survey lines discontinued by CalCOFI in the 1980s are now regularly occupied on a quarterly basis under a cooperative relationship established between NOAA and the Monterey Bay Aquarium Research Institute, the Navy Post Graduate School, and the University of California, Santa Cruz. A historic gap in marine observations on the Pacific Coast occurring in northern California may soon be filled as well. A NOAA fisheries position was recently filled at Humboldt State University (HSU) to aid HSU in implementing PaCOOS surveys in northern California. When HSU begins their part of the work, the coast-wide ecosystem observing system, based on plankton-based hydrographic surveys as envisioned in 2001, will be established. Other PaCOOS events in 2005 included: adding two additional NOAA organizations to the Board of Governors (NESDIS and OAR), thereby strengthening the participation of NOAA in PaCOOS; initiation of long-term planning of data integration and access; and planning of a coast-wide demonstration project focusing on climate and the dynamics of the coast-wide stocks of sardine, hake, and euphausiids.

MOLECULAR ROCKFISH LARVAL IDENTIFICATION

Russell Vetter and staff at SWFSC have continued to make genetic identification of fish eggs and larvae a priority. To this end, John Hyde (Scripps Institution of Oceanography) has been developing genetic markers for the identification of *Sebastes* larvae. In conjunction with Cynthia Taylor (Scripps Institution of Oceanography), all of the *Sebastes* spp. collected during the 1999 CalCOFI cruises have been processed. Using the new molecular method, the number of identifiable species has increased from five to 28 with only 2% of the larvae remaining unidentifiable to the species level. Interestingly, the samples are dominated by two species, *S. hopkinsi* and *S. ensifer*, which together comprise >60% of the larvae.

COAST-WIDE SARDINE SURVEY

A Baja California to British Columbia coast-wide survey was first proposed at the 2000 Trinational Sardine Forum (TSF) held 29 November–1 December in Ensenada, Baja California, Mexico. The initial goal of this survey was to obtain estimates of total biomass of Pacific sardines off of the American continent from northern Baja California to British Columbia. Routine biomass estimates conducted in April off California and Mexico and those made off the Pacific Northwest in July may be double counting sardines as they are a migratory species. A synoptic survey would prevent such double counting and was proposed again at the 2004 TSF on 18 November 2004 in La Jolla, California. The data from this coast-wide survey can be used to evaluate not only Pacific sardines but also other pelagic fish populations off the western American continent. Genetic samples and age-length distribution can be used to infer movement patterns and stock structure.

Our current proposal specifies a coast-wide (U.S. EEZ off the states of California, Oregon, and Washington), near-synoptic (two-ship) survey of Pacific sardines to be conducted during April 2006. Tentative plans also include complementary surveys by Mexican and Canadian scientists of waters off northern Baja California and southern British Columbia. The objectives of the surveys will be to describe the spatial distribution of eggs, larvae, and adults, obtain measurements of egg production and adult fecundity required for an estimate of spawning biomass, and to collect environmental data that may be useful for describing spawning habitat. The survey design will consist of regularly spaced stations along a series of inshore/offshore transects following an extended CalCOFI pattern. Primary station observations will include: a) pelagic trawl samples of adult fish; b) plankton net samples of eggs, larvae, and zooplankton; and c) vertical profiles of temperature, salinity, oxygen, and chlorophyll. Primary transect observations will include: a) continuous egg pump samples; b) continuous multi-frequency acoustic samples of adult fish; and c) continuous measurements of sea-surface and meteorological conditions. Other observation protocols may be added as time, space, and personnel allow.

The data collected on this coast-wide survey will serve a variety of purposes. Egg data collected from CUFES and temperature data can be used to examine the spatial distribution of eggs of pelagic species with sea surface temperatures. Preliminary estimates of biomass of Pacific sardines can be computed based on data from trawl and acoustic surveys. Spawning biomass, as well as size and age distribution of Pacific sardines off Mexico, the U.S., and maybe British Columbia, can be obtained from egg and larval data plus adult reproductive specimens from the trawls. Estimates of absolute total biomass and spawning biomass of Pacific sardines would greatly benefit the stock assessment. Spatial distributions of eggs, larvae, and adult populations, together with oceanographic conditions, would contribute to a better understanding of population dynamics. The size distribution, if different between inshore and offshore, could be used to estimate availability to the fisheries in the stock assessment. Finally, determining stock structure through genetics is essential for updating fishery management strategies.

SIO HIGHLIGHTS

CalCOFI cruises are near capacity with ancillary programs, several of which were initiated this year. All of these programs broaden our understanding of the ecosystem far beyond that provided by the CalCOFI time-series itself.

Professor John Hildebrand of Scripps Institution of Oceanography has received four-year funding from ONR to make quantitative observations of cetaceans in the CalCOFI region, both with moored acoustic recorders and acoustic and visual observations from CalCOFI ships. The intent is to relate cetacean location to mesoscale oceanographic features. This is a graduate student project, and shipboard observations began on the April 2004 cruise.

Funding from the Southern California Coastal Ocean Observing System (SCCOOS) allows CalCOFI to extend surveys toward the coast. Since the July 2004 cruise, seven inshore stations (20 m depth) have been occupied, one at the end of each cardinal line and one midway between. Data from these stations will provide a bridge between the offshore observations of CalCOFI and the nearshore observations of SCCOOS. SCCOOS funding is also supporting the development of a bio-optical approach to estimating primary productivity.

CalCOFI 0411, on the R/V *Roger Revelle*, marked the initiation of research of the California Current Ecosystem/Long-Term Ecological Research Program. Funded by NSF in five-year, renewable increments, this program has three interdependent components: time-series observations (CalCOFI), experimental process cruises, and modeling studies. CCE/LTER adds several new measurements to the regular CalCOFI cruises.

Recently, a Moore Foundation award was received by Mark Ohman and Russ Davis to enhance the resolution of the quarterly surveys with two new instruments. Autonomous ocean gliders along two CalCOFI lines would "fly" continuously, providing ecological information from the upper ocean between cruises. Spatial augmentation during cruises will be provided with a shipboard free-fall Moving Vessel Profiler that will provide nearly continuous spatial coverage of the upper ocean between stations. These two instruments will significantly improve our ability to resolve changes in hydrographic structure and plankton communities. Deployment is expected to begin this fall (2005).

As always, the quarterly cruises serve as research platforms for graduate student research. Two ongoing student projects in addition to the whale project are a study of dissolved organic carbon cycling and a study of the utilization of iron and nitrate by phytoplankton in the Southern California Bight.

In anticipation of the Pacific Coast Ocean Observing System (PaCOOS), Scripps has continued to advance our data processing procedures with the final goal of a quasi-autonomous computer-based system that maintains our traditional high standards of data quality. This will make CalCOFI data more quickly available and more easily communicated. All cruises from 2004 are currently available online at <www.calcofi.org/newhome/data/data.htm>.

A strategic effort in preparation for PaCOOS has been the development of a "white paper" that provides a comprehensive review and summary of the vast and disparate data now collected by CalCOFI at Scripps and a plan for an information management approach that will facilitate integration of the CalCOFI dataset into the larger PaCOOS system. CalCOFI provides a spectrum of the data-management challenges that will need to be addressed by PaCOOS, and it is anticipated that identifying, articulating, and addressing these collaboratively on the CalCOFI scale will inform the development of the more complex federated system.

CDFG HIGHLIGHTS

The Marine Life Protection Act (MLPA) was reinvigorated with the combined efforts of the CDFG and the Resources Agency coupled with private donations through the Resources Legacy Fund Foundation (RLFF). This new initiative will build on the progress and lessons learned in the earlier efforts. In 2004, the MLPA initiative named an eight-member Blue Ribbon Task Force (BRTF) to serve as the principle body for making recommendations to the Department of Fish and Game Commission. In support of the task force, a Science Advisory Team was named that included distinguished marine biologists, oceanographers, and socioeconomics professionals from the West Coast. A steering committee populated by CDFG staff and task force staff hired on through the RLFF also aids the task force. In 2005, the BRTF will define a region along the central coast to serve as the first stage of Marine Protected Area (MPA) implementation in California as mandated in the MLPA. Once the central coast region is defined and accepted by the CDFG Commission, a Central Coast Regional Stakeholder Group will be named to represent major marine interests in the region. This group will work with a sub-team from the Science Advisory Team to draft alternative MPA network proposals. This first phase of establishing a network of MPAs along the central coast is slated to be complete by mid-2006 with the rest of the state completed in stages until the final completion date in 2011. More information can be found on the MLPA initiative process at <www.dfg.ca.gov/mrd/mlpa/index.html>.

In the legislature, FGC 8494 was passed in 2004 and requires that any vessel using bottom trawl gear in state-managed halibut fisheries shall possess a halibut bottom trawl permit. It also specifies a minimum landing requirement and qualifying period, transfer guidelines, and fee levels.

Each year, the Commission adopts state regulations that conform to the federal regulations for commercial and recreational ocean salmon and commercial and recreational groundfish. There are also annual regulations cycles for commercial herring and herring roe on kelp. Additional Commission 2004 regulation changes were for bag limits for rockfishes, cabezon and greenlings fishery closures, restricted access fishery for spot prawn, retention of black rockfish, spot prawn trawl conversion program, lingcod season, size and bag limits, cabezon total allowable catch and cumulative trip limits, nearshore fishery trap gear limitations, use of dip nets in the commercial nearshore fishery, and marine protected areas.

Implementation of the Nearshore Fishery Management Plan (NFMP) focused on efforts to increase our knowledge of plan species through formal stock assessments, refining methods for monitoring landings, implementing the restricted access program, and determining the amount of appropriate habitat for plan species in existing Marine Protected Areas (MPAs). UCSC, CDFG, and NMFS staff completed the first-ever, peer-reviewed stock assessment for California sheephead (*Semicossyphus pulcher*), a state-managed, protogynous hermaphroditic species that occurs primarily south of Point Conception. When this unusual life history characteristic is accounted for in the assessment model, and biomass of both mature males and females is considered, the stock is determined to be at 31% of the unfished level. Managers developed management measures (e.g., seasons, trip limits, etc.) for nearshore species for 2005–06 that provided more fishing opportunities, while protecting overfished species, using information from stock assessments and constituent input. The Restricted Access program has been fully implemented and permit appeals have been completed. The first year of the full-restricted access program has experienced an attrition rate of about seven percent in the number of permittees fishing for the shallow nearshore species (cabezon, California sheephead, greenlings, California scorpionfish, and black-and-yellow, China, gopher, grass, and kelp rockfishes). The Deeper Nearshore Species Fishery Permit was first required in 2003 to take black, blue, brown, calico, copper, olive, quillback, and treefish rockfishes and has had an attrition rate of nine percent. Knowledge of appropriate habitat in existing MPAs will further efforts to base management on methods using fish densities in reference areas as described in the NFMP. Cataloguing of appropriate habitat has been initially directed toward southern California nearshore areas and will expand northward in 2005.

The Fish and Game Commission adopted the Market Squid Fishery Management Plan (MSFMP) in 2004, which went into effect in March 2005. The MSFMP was drafted to be flexible enough to adapt to changes in both the environment and economic conditions yet ensure for the long-term sustainability of squid populations. Key elements within the plan include: 1) seasonal catch limits; 2) maintaining an active monitoring program; 3) weekend closures; 4) gear restrictions requiring light shields and wattage limits during fishing; 5) a restricted access program; and 6) establishing a seabird closure in the Gulf of the Farallones National Marine Sanctuary. This plan outlines how management decisions will be made while allowing for adaptive management to stochastic fishery conditions. In addition, the Commission can react quickly to volatility within the fishery without the need for plan amendments, which can slow response time. It will also provide the Commission specific guidelines for making management decisions.

The Department completed analysis of the Tanner crab experimental fishery and produced a summary report including recommendations for management of an emerging fishery. The report included biomass estimates and harvest guidelines for the emerging fishery. After the sale of the Stornetta property in northern California, an assessment was completed comparing abalone/invertebrate resources there with those at Moat Creek in spring 2004. Commercial sea urchin management continued with the market sampling and logbooks programs and production of an annual fishery report. The spot prawn trawl to trap conversion program was completed in 2004.

The Cooperative Research and Assessment of Nearshore Ecosystems (CRANE) group, with funding from the California Impact Assistance Program, completed surveys of fish and invertebrates at 68 kelp bed sites from Monterey to San Diego and at the Channel Islands in the summer of 2004. We are now compiling the survey data and historical data, some of which goes back to the 1970s. We expect to have a descriptive report of the data and a manuscript for submission in 2006.

In the past two years, we have been developing protocols using Remotely Operated Vehicles (ROV) to quantitatively measure fish populations in areas beyond diver depths. We are now using our methods to collect data for the Channel Islands MPA Monitoring Program. In November 2003 and May 2004 we did exploratory surveys of 14 sites, and in September 2004 we quantitatively surveyed five sites. We are now seeking funding for a survey of 10 additional sites in the summer of 2005.

Aerial surveys of kelp bed canopy on the mainland coast and the Channel Islands were completed in the summers of 2002 through 2004, and a survey is planned for 2005. The 2002 and 2003 data are posted on the CDFG web site. Data from 2004 will be posted in September 2005.

The Ocean Salmon Project (OSP) estimates ocean salmon harvest and fishing effort by major port and half-month periods. In addition, the program collects 20% of the catch to estimate the coded-wire-tagged (CWT) salmon contribution rates to California ocean salmon fisheries. In 2004, the ocean salmon fisheries were closer to shore than in 2003 and were centered on the San Francisco port area (60% of all estimated landings). Estimated commercial landings were similar to 2003 (approx. 500,800 salmon), but the recreational landings estimates almost doubled from the 2003 estimates (approx. 220,200 salmon). The estimated recreational harvest was greater than the effort (approx. 215,700 angler days fished) in 2004. OSP collected and processed heads from approximately 17,000 adipose fin-clipped salmon for CWT's.

A joint NMFS and CDFG nearshore groundfish logbook program was initiated in 2004. Nearshore fishers, industry representatives, and agency personnel collaborated during a workshop to plan the voluntary program. A pilot study was initiated in phases starting with one port in each of the four management regions (Crescent City, Fort Bragg, Morro Bay, and Santa Barbara). Invitations were sent to all nearshore fishery permit holders inviting them to participate in the program.

The Aquaculture, Disease, and Aquatic Nuisance Species mandate continued efforts in 2004 to assure eradication of the invasive algae *Caulerpa taxifolia* from two California lagoons and eradication of the abalone-infesting sabellid polychaete from abalone farms and display facilities throughout the state. Disease control at the Ocean Resources Enhancement Program's white sea bass hatchery allowed the release of over 240,000 juveniles, a new record number, this year.

KUDOS

The seagoing personnel of the SWFSC's Fisheries Resources Division, SIO's Integrative Oceanography Division, and CDFG's Marine Region all contributed, through their dedication and diligence, to the success of CalCOFI's quarterly fieldwork. The CalCOFI 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 F/V *Frosti*, and the University of California's R/Vs *New Horizon* and *Roger Revelle*.

We also thank the reviewers of contributed papers in volume 46: Steve Cadrin, Francisco Chavez, Dave Checkley, Miguel Cisneros, Ray Conser, Stewart Grant, Kevin Hill, John Hunter, Larry Jacobson, John Largier, Bertha Lavaniegos, Daniel Lluch-Belda, Nancy Lo, Jerry Norton, Kevin Piner, Ruben Rodriguez-Sanchez, Gretchen Rollwagen-Bollens, Jake Schweigert, Paul Smith, Chuck Trees, Russ Vetter, and Cara Wilson. We are especially grateful to Sarah Shoffler for her professional work in editing this volume of *CalCOFI Reports*.

The CalCOFI Committee:
Anne Allen, CalCOFI Coordinator
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Elizabeth Venrick, UCSD
Laura Rogers-Bennett CDFG

REVIEW OF SOME CALIFORNIA FISHERIES FOR 2004: COASTAL PELAGIC FINFISH, MARKET SQUID, SEA URCHIN, LOBSTER, SPOT AND RIDGEBACK PRAWN, GROUNDFISH, HIGHLY MIGRATORY SPECIES, OCEAN SALMON, NEARSHORE LIVE-FISH, PACIFIC HERRING, AND RECREATIONAL

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SUMMARY

In 2004, commercial fisheries landed an estimated 137,329 metric tons (t) of fishes and invertebrates from California ocean waters (fig. 1). This represents an increase in landings of over 9% from the 125,687 t landed in 2003 and a 46% decline from the 252,568 t landed in 2000. Following recent trends, the preliminary ex-vessel economic value of commercial landings in 2004 was $131 million, a 2% increase from the $128 million in 2003, and a 25% increase from $105 million in 2002.

The Pacific sardine fishery was the largest in the state by volume, at over 44,000 t, although the Dungeness crab fishery had the highest ex-vessel value at nearly $41 million. The ex-vessel value for the sardine fishery was nearly $4 million, ranking it seventh. Market squid landings were both second in volume, at just over 40,000 t, and ex-vessel value, at nearly $20 million. Other top-five California landings included Dungeness crab at over 11,000 t, northern anchovy at 6,700 t, and sea urchin at 5,500 t. Besides Dungeness crab and market squid, the top five California landings in terms of ex-vessel value included Chinook salmon at $17.7 million, sea urchin at $7.3 million, and California spiny lobster at $5.8 million.

Landings of California spiny lobster in 2004 were the highest since 1997 at 375 t. The regulatory process making lobster trap permits transferable was started by the California Fish and Game Commission (Commission). Spot prawn landings increased in 2004 by 25% over 2003 landings to 101 t. Only trap gear has been allowed in the fishery since 2003, and a conversion program to allow trawl fishermen into the restricted access trap fishery was instituted. Ridgeback prawn landings in 2004 were at the lowest harvest since 1978 at 28 t.

California's commercial groundfish harvest for 2004 was over 12,000 t, consisting mainly of Pacific whiting, Dover sole, rockfishes, and sablefish. Ex-vessel value of groundfish landings for 2004 was $13.7 million, a decrease of $1.1 million from 2003. In addition, the Pacific Fisheries Management Council (PFMC) and NOAA Fisheries removed Pacific whiting from an overfished status and consider the stock to be officially rebuilt.

For highly migratory species (HMS), commercial and recreational landings of albacore decreased 22% and 27%, respectively; commercial yellowfin tuna landings were slightly higher than 2003, whereas recreational landings of yellowfin doubled; and, commercial landings of shark species decreased. Revisions to the HMS fishery management plan were adopted in March 2004 by the PFMC and NOAA Fisheries.

A new program to monitor the recreational catches of marine fishes in California entitled the California Recreational Fisheries Survey (CRFS) was implemented by the California Department of Fish and Game (CDFG) in January 2004. CRFS was created to provide more accurate recreational fisheries information in order to make in-season management decisions and avoid in-season closures.

In 2004, the Commission undertook 22 rule-making actions that address marine and anadromous species. The Commission also adopted the Market Squid Fishery Management Plan which initiates fisheries control rules, a restricted access program, and a seabird closure within the Gulf of the Farallones National Marine Sanctuary for the 2005–06 season. In addition, the Commission instituted a Spot Prawn Conversion Program which allowed several of the previously excluded spot prawn trawl vessels into the restricted access trap fishery.

Coastal Pelagic Finfish

Pacific sardine (*Sardinops sagax*), Pacific mackerel (*Scomber japonicus*), jack mackerel (*Trachurus symmetricus*), and northern anchovy (*Engraulis mordax*) are known as coastal pelagic species (CPS) of finfishes. These species are jointly managed by the PFMC and NOAA Fisheries. During 2004, combined commercial landings of these four species totaled 55,682 t (tab. 1), and the ex-vessel value exceeded $5.4 million (U.S.). The Pacific sardine fishery is by far the most valuable fishery among these four species.

Pacific Sardine. The Pacific sardine fishery extends from British Columbia, Canada southward into Baja California, México (BCM). Although the bulk of the catch is landed in southern California and Ensenada, BCM, landings in the Pacific Northwest are increasing. The Pacific sardine harvest guideline (HG) for each cal-

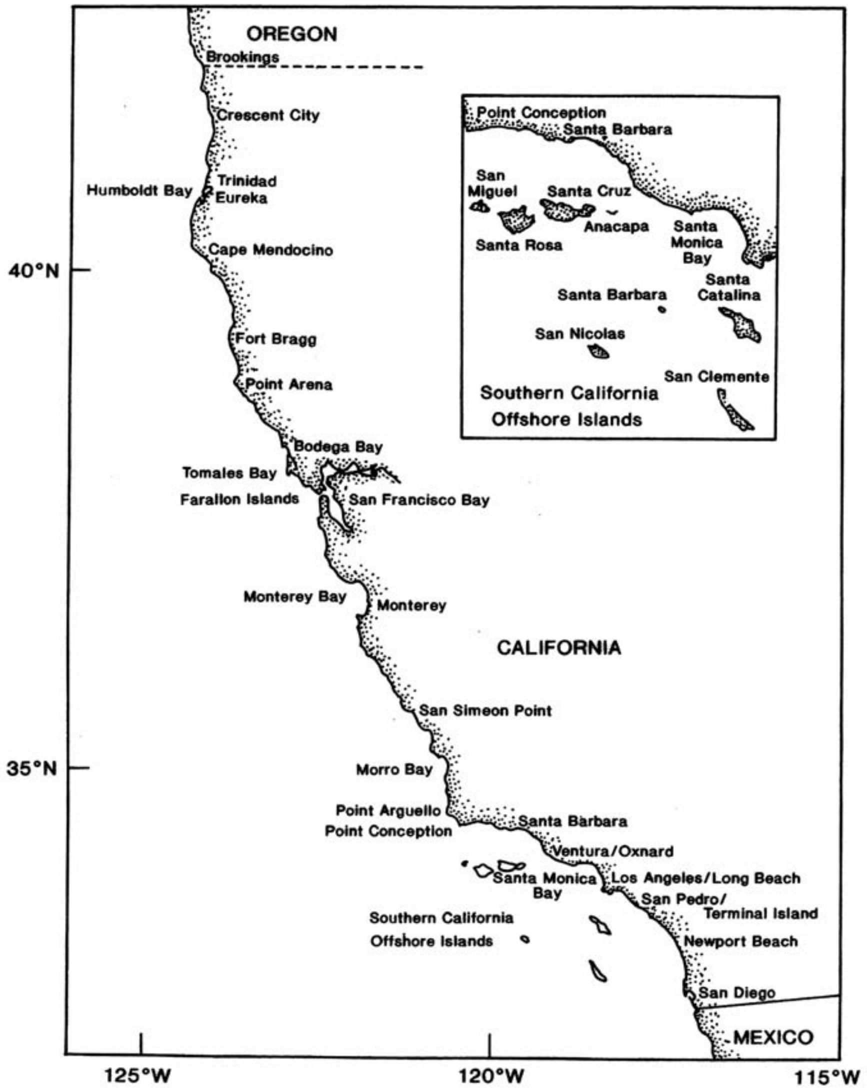

Figure 1. California ports and fishing areas.

endar year is determined from the previous year's stock biomass estimate (≥1-year-old fish on 1 July) in U.S. and Mexican waters. The 1 July 2003 stock biomass estimate for Pacific sardine was 1.1 million t and the recommended U.S. HG for the 2004 season was 122,747 t. The southern sub-area (south of 39°00'00" latitude to the U.S.-Mexican Border) received two-thirds of the HG (81,831 t) and the northern sub-area (north of 39°00'00"N latitude to the U.S.-Canadian Border) received one-third (40,916 t). On 1 September, 80% (54,407 t) of the uncaught HG was reallocated to the southern sub-area, and 20% (13,602 t) was reallocated to the northern sub-area. On 1 December, the total remaining HG was opened coastwide, and by 31 December 2004, 81% (99,526 t) of the HG had been caught coastwide.

The development of a fair and balanced allocation scheme for Pacific sardine fisheries along the North American West Coast continues to be a top priority for the managing agencies involved. The PFMC is scheduled to adopt a preferred alternative in June 2005, so the new allocation can be in place for the 2006 fishing season.

During 2004, a total of 44,293 t of Pacific sardine, valued at more than $3.9 million, was landed in California. This represents a 22.6% increase in commercial sardine landings over 2003 (34,292 t). In California, commercial sardine landings averaged 43,235 t over the ten-year period from 1994–2004 (fig. 2). As in previous years, most (88.4%) of California's 2004 catch was landed in the Los Angeles (53.5%; 23,677.1 t) and Monterey (34.9%; 15,443.6 t) port areas (tab. 2). During 2004, a total of 27,841 t of sardine product was exported from California to 25 countries. Most of this product was exported to Japan (11,919 t) and Australia (9,830 t), which represents more than 77% of the total export value of just under $14.6 million.

Oregon's sardine landings have increased steadily over

TABLE 1
Landings of Coastal Pelagic Species 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	2,895	68,646
1999	56,747	5,179	9,527	963	2,207	91,950	164,945
2000	53,586	11,504	21,222	1,135	3,736	118,827	209,144
2001	51,811	19,187	6,924	3,615	2,715	86,203	170,080
2002	58,353	4,643	3,367	1,006	3,339	72,878	143,586
2003	34,292	1,547	3,999	155	1,780	44,965	88,741
2004	44,293	6,793	3,569	1,027	1,596	40,324	99,606

TABLE 2
Landings of Pacific Sardine and Pacific Mackerel at California Port Areas in 2004

	Pacific Sardine		Pacific Mackerel	
Area	Landings t	% Total t	Landings t	% Total t
Eureka	24	0	0	0
San Francisco	370	1	0	0
Monterey	15,444	35	490	14
Santa Barbara	4,734	11	70	2
Los Angeles	23,677	54	3,012	84
San Diego	45	0	0	0
Total	44,293	100	3,572	100

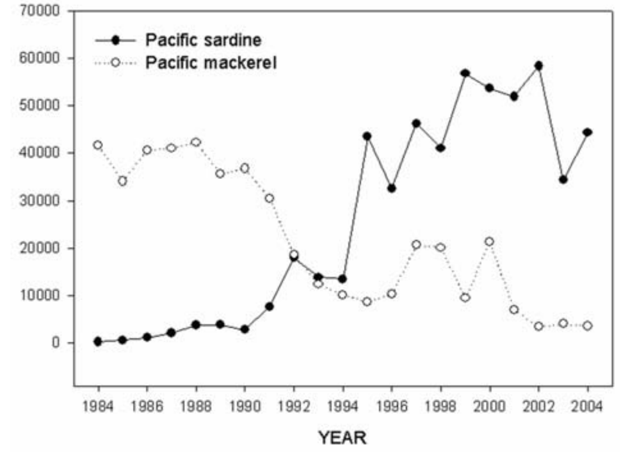

Figure 2. California commercial landings of Pacific sardine (*Sardinops sagax*) and Pacific mackerel (*Scomber japonicus*), 1984–2004.

the past few years (fig. 3). A total of 36,111 t of sardines with an ex-vessel value that exceeded $4.8 million was landed into Oregon during 2004. This represents a 30% increase over 2003 (25,258 t). In contrast, Washington's 2004 sardine landings decreased by 25% to 8,934 t in 2004, compared to 11,920 t in 2003 (fig. 3).

Pacific Mackerel. Although Pacific mackerel is occasionally landed in Oregon and Washington, the majority of landings are made in southern California and Ensenada, BCM. The U.S. fishing season for Pacific mackerel runs from 1 July to 30 June. At the beginning of the 2004–05 season (1 July 2004), the biomass was estimated to be 81,383 t and the HG was set at 13,268 t. Because mackerel are often landed incidentally to other CPS, the HG was divided into a directed fishery (9,100 t) with the remaining HG (4,168 t) set-aside for incidental catch (limited to 40% of a mixed load).

California landings of Pacific mackerel have been in decline since the early 1990s (fig. 2). Since 2002, annual landings have averaged 3,645 t. In 2004, 3,569 t of Pacific mackerel were landed in California with an ex-vessel value of $549,253. Eighty-four percent (3,012 t) was landed in the Los Angeles port areas (tab. 2).

A total of 1,311 t of mackerel product was exported from California to 12 countries worldwide. Most (60%) of this product was exported to Japan. California's export revenue for mackerel products in 2004 was nearly $1.3 million.

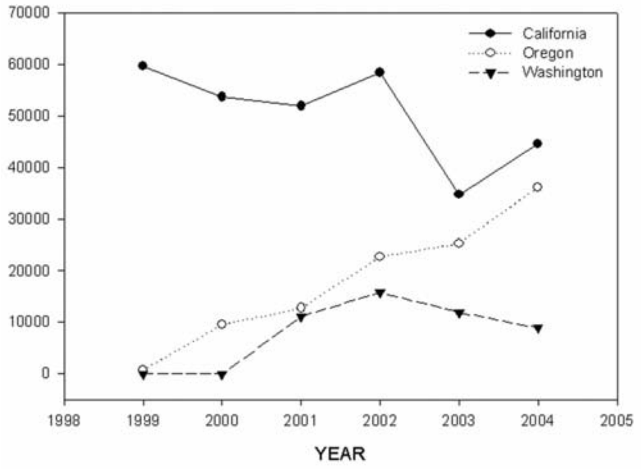

Figure 3. Commercial landings of Pacific sardine (*Sardinops sagax*) in California, Oregon, and Washington, 1999–2004 (PacFIN data).

Since 1999, an average of 219 t of Pacific mackerel has been landed in Oregon, and 107 t was landed during 2004. In Washington, annual landings of mackerel (unspecified species) have averaged 174 t since the year 2000; however, just 22 t were landed during 2004.

Jack Mackerel. Landings of jack mackerel in California were considerably higher in 2004 (1,027 t) than the previous year (155 t); however, they were very similar to 2002 landings (1,006 t). Ex-vessel revenues in 2004 totaled $246,742, a 78% increase from 2003. In Oregon, landings of jack mackerel totaled 125.8 t with an ex-vessel value of $17,262. This represents a 41% increase in landings from 2003 and a 93% increase from 2002. There were no reported landings of jack mackerel in Washington during 2004.

Northern Anchovy. Over the past decade, landings of northern anchovy in California have varied widely. This trend continued in 2004, when landings, which totaled 6,793 t, increased by 77% over the previous year (1,547 t). Ex-vessel revenues for northern anchovy totaled $700,593, making this species the second most valuable CPS finfish in 2004 behind Pacific sardine. In terms of total ex-vessel revenues realized by the four CPS finfish, Pacific sardine represented 72.5%, northern anchovy 13%, Pacific mackerel 10%, and jack mackerel 4.5%.

A total of 53 t of anchovy product valued at $280,141 was exported from California during 2004. Eighty-five percent of California's anchovy export product was shipped to two countries: China (22 t; $139,179) and Australia (23 t; $84,217). In 2004, no northern anchovy was landed in Washington; however, 39.1 t valued at $3,111 was landed in Oregon.

Krill. Following a request from the National Marine Sanctuaries to prohibit krill fishing in the exclusive economic zone (EEZ) around the three marine sanctuaries off central California, the PFMC will initiate an amendment to the CPS FMP to include krill as a management unit. To facilitate amending the CPS FMP, an alternatives analysis for krill management will be written in the general format of an environmental assessment. Currently, krill fishing is prohibited within the state waters of Washington, Oregon, and California.

INVERTEBRATE FISHERIES

Market Squid

Market squid (*Loligo opalescens*) continued to be one of the largest fisheries in the state. Statewide landings were estimated at 40,324 t, 10% less than 2003 (44,965 t) and 66% less than the record high set in 2000 (118,827 t) (fig. 4). The ex-vessel price ranged from $150–750/t, with an average of $450/t. The 2004 ex-vessel value was approximately $19.9 million, a 22% decrease from 2003 ($25.4 million).

The fishing permit season for market squid runs from 1 April through 31 March the following year. A northern fishery occurs during the spring and summer and is centered in Monterey Bay. A southern fishery occurs during the fall and winter off the Channel Islands and coastal southern California. During the 2004–05 season (as opposed to the 2004 calendar year), 46,211 t were landed, 15% less than the 2003–04 season (54,636 t) (fig. 5).

The northern fishery catch levels declined to historical levels during the 2004–05 season (fig. 5). Only 6,571 t were landed, a 62% decrease from the 2003/2004 season (17,399 t). Landings began in March and continued through November; however, the majority of landings occurred in May and June. Bad weather, poor squid quality, and concern over fishing pressure in Monterey Bay reduced fishing activity throughout the season. In July and August, water temperatures rose within the bay, further reducing landings. By September, fishing slowed considerably, and vessels began heading to the Channel Islands to participate in the southern fishery.

The southern fishery once again surpassed the northern fishery with 39,640 t landed (86% of the catch) during the 2004–05 season (fig. 5). This was a 6% increase from the 2003–04 season (37,237 t). Landings occurred throughout the season with the bulk of squid caught around the northern Channel Islands. During the late summer months, squid became scarce because of warm water temperatures, so vessels headed north to look for squid along the mainland coast near Point Conception and to participate in the northern fishery. Squid landings slowly increased again in November and remained steady throughout the remainder of the season despite heavy rain storms and overcrowding by vessels at Santa Cruz and Santa Rosa Islands. In March 2005, fishermen found it increasingly difficult to find the large squid

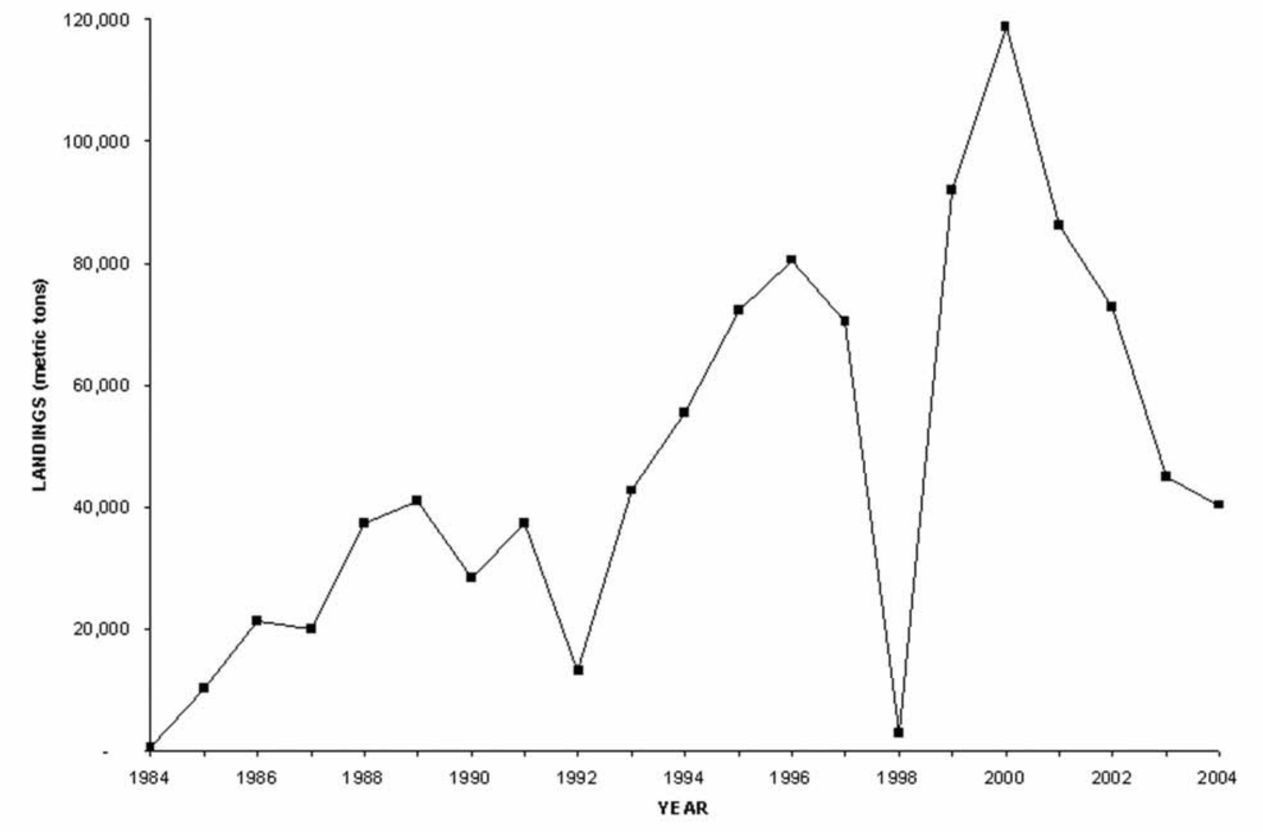

Figure 4. California commercial market squid landings, 1982–2004.

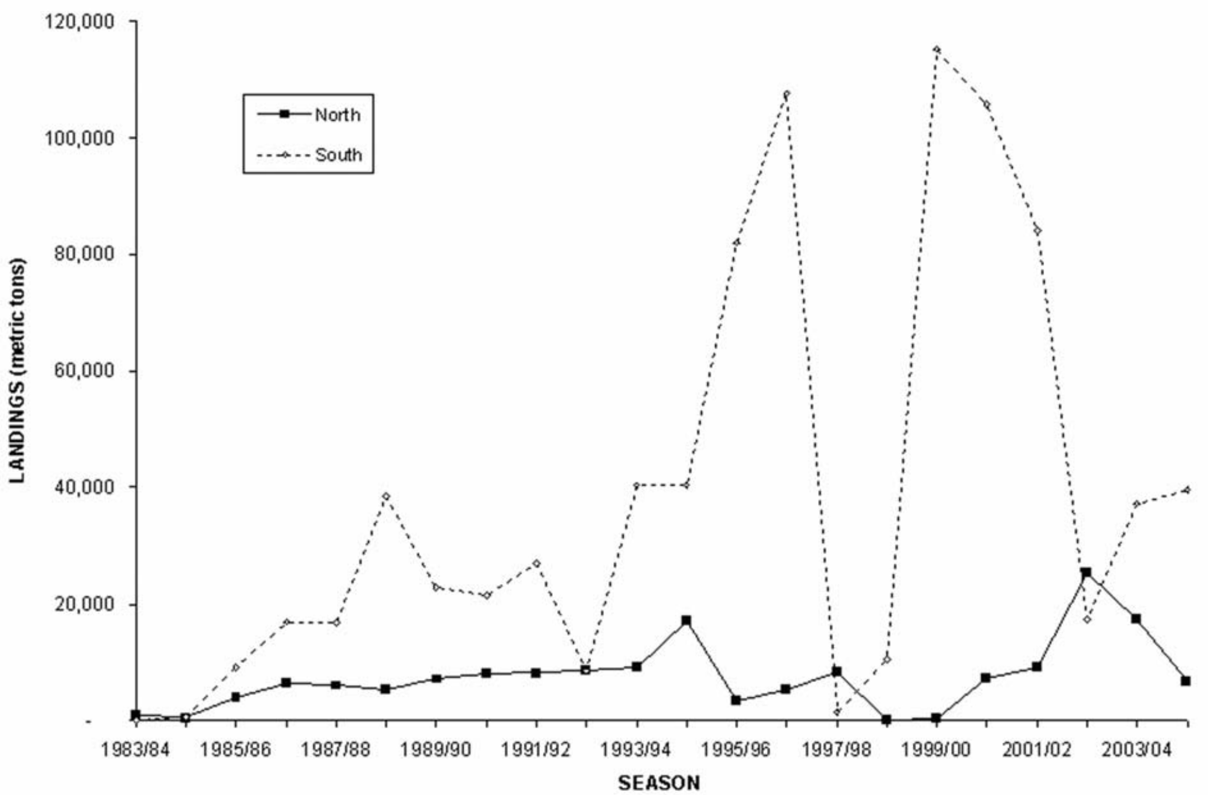

Figure 5. Comparison of market squid landings for northern and southern fisheries by fishing season (1 April–31 March), from the 1982–83 season to 2004–05 season.

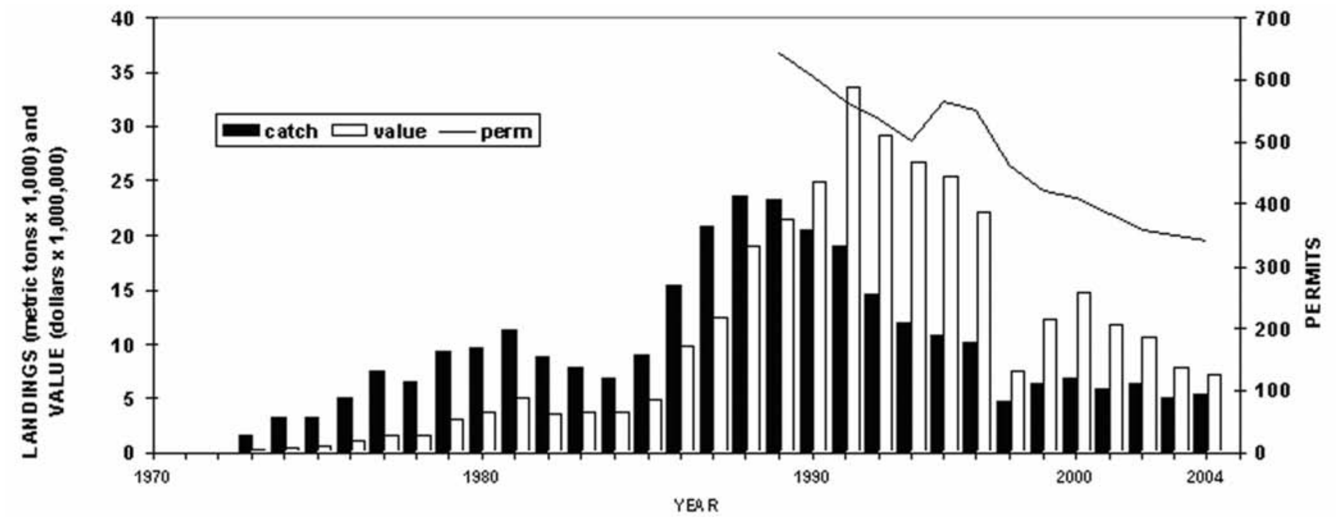

Figure 6. California commercial red sea urchin fishery catch, value, and number of permits, 1971–2004.

favored by the markets, so many switched to targeting Pacific sardine and mackerel or headed north to Moss Landing and Monterey.

Market squid remains an important international commodity. Squid is used domestically for food and bait and is packed and processed for export. In 2004, approximately 13,580 t of market squid were exported for a value of $16.9 million. Asian countries were the main export market, with China and Japan taking about 60% of the trade.

In August and December of 2004, the Fish and Game Commission adopted the Market Squid Fishery Management Plan (MSFMP) and its implementing regulations, Sections 53.00-53.03, 149.00-143.00, Title 14, California Code of Regulations (CCR), which went into effect on 28 March 2005. The goals of the MSFMP are to provide a framework that will be responsive to environmental and socioeconomic changes and to ensure long-term resource conservation and sustainability. The tools implemented to accomplish these goals include: 1) setting a seasonal catch limit of 118,000 short tons (107,048 t) to prevent the fishery from over-expanding; 2) maintaining monitoring programs designed to evaluate the effect of the fishery on the resource; 3) continuing weekend closures that provide for periods of uninterrupted spawning; 4) continuing gear regulations regarding light shields and wattage used to attract squid; 5) establishing a restricted access program that includes provisions for initial entry into the fleet, permit types, permit fees, and permit transferability that produces a moderately productive and specialized fleet; and 6) creating a seabird closure restricting the use of attracting lights for commercial purposes in any waters of the Gulf of the Farallones National Marine Sanctuary. Under this framework, the Commission will be able to react quickly to changes in the market squid population off California without the need for a full plan amendment. It will also provide the Commission specific guidelines for making management decisions. These guidelines will then allow for other management strategies, which would effectively achieve the goals and objectives of the MSFMP and Marine Life Management Act.

Sea Urchin

Statewide landings of red sea urchins (*Strongylocentrotus franciscanus*) in 2004 were estimated at 5.36 t with an ex-vessel value of $7.1 million (fig. 6). This represents an increase of 6.4% over the previous year. However, northern California landings continued to decline, dropping another 39% compared to 2003, to 0.61 t (11% of the statewide total). Point Arena led northern ports for the second consecutive year, supplanting Fort Bragg as the top northern port during the first 20 years of the fishery.

The 2004 southern California landings increased by 18%, (4.75 t) from 2003. The long-term 1975–2004 average catch for the southern part of the state is 7.53 t. Santa Barbara landed 2.59 t in 2004, a 32% increase over the previous year, making it the number one port in the state with almost half of the state's landings. However, based on market receipts, effort in Santa Barbara was up by only 16%, indicating that CPUE had increased significantly, by 320 kilograms per receipt, over the previous year. Santa Barbara landings increased as a direct result of the return of the northern Channel Islands as the primary southern California fishing area, after a dip in 2000 and 2001. This recovery also followed the decline of the southern Channel Islands from over 2.36 t caught in 1995 to about 0.32 t in 2004.

Poor market conditions continued to affect the industry, especially in northern California, where premium prices are often lower than those paid in the southern

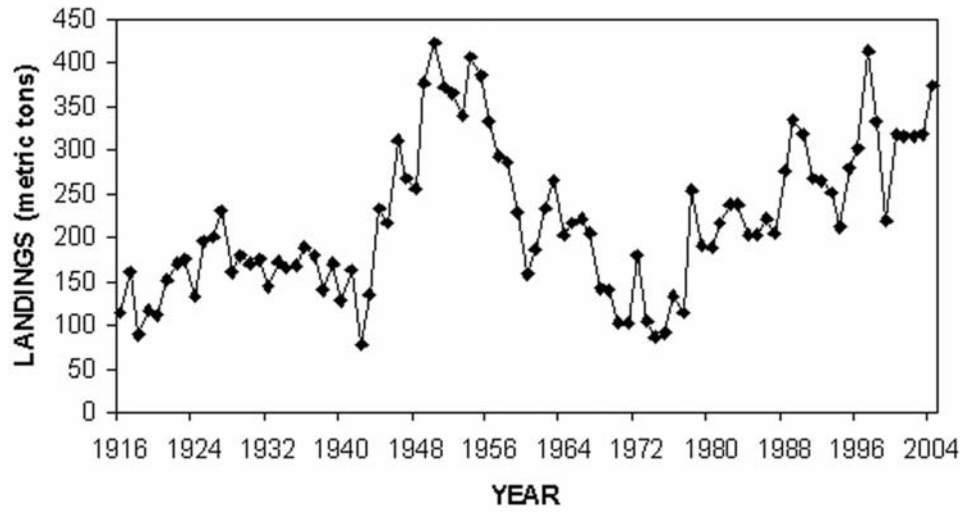

Figure 7. California commercial landings of california spiny lobster, 1916–2004.

part of the state. By the end of 2004, northern California was left with only one major dealer/processor. While some dealers have successfully increased the domestic market share in recent years, in response to weakened Japanese demand, domestic sales have not replaced that lucrative market. Sea urchin ex-vessel prices have been depressed for a number of years, with 24% of the catch selling for $0.66–$0.86 per kilogram, 24% selling for $1.54–$1.74 per kg, and less than 5% of the catch fetching over $2.20 per kg. When adjusted for inflation, the 2004 catch yielded about one-half of the 1995 catch on a per-unit basis. Coupled with rising fuel costs, these low prices have combined to lead many divers to cease fishing until the economics improve.

There were 340 sea urchin permits issued in 2004, down by nine from the previous year (fig. 6). The median age of active urchin divers in 2004 was 48 years, with the median years of service at 12. The aging of the sea urchin diver population has been a growing concern of the industry in recent years. The issue of permit transferability is being debated more actively as older divers look to retirement or hope to pass on their permit to younger family members. This is especially true in northern California where market forces and more challenging diving conditions have reduced the working diver pool to only 20 active divers (those landing more than 4.5 t annually).

The Sea Urchin Fishery Advisory Committee (SUFAC) continued to support urchin resource research in 2004 by funding a long-term study of sea urchin larval recruitment by Dr. Stephen Schroeter. Results indicate that since 1990 larval settlement responds to the changes in large-scale oceanographic conditions associated with El Niños, but these responses differ markedly between northern and southern California. In northern California, large settlement events occurred during the relaxation of upwelling associated with El Niño conditions in 1992, 1993, 1997, and 1998. By contrast, settlement in southern California was lower during El Niño events and increased following the end of the El Niño conditions.

The SUFAC also continued with development of its "barefoot ecologist" program, a collaborative effort between industry divers, scientists, and CDFG to provide a low-cost mechanism whereby urchin divers collect reliable size-frequency and density data on red sea urchin populations using scientifically valid protocols. Problems yet to be resolved with this program include designing an easy-to-use, accurate sea urchin measuring device and a reliable system for measuring habitat area.

California Spiny Lobster

Landings in 2004 for California spiny lobster (*Panulirus interruptus*) totaled 375 t, the highest landings since 1997 (fig. 7). Increases and decreases in landings are not unexpected in a fishery that is strongly influenced by the weather and El Niño and La Niña events. In 2004, landings were almost split evenly between San Diego (37%) and Santa Barbara/Ventura County ports (36%), with Los Angeles/Orange County ports (27%) contributing just over a quarter of the landings. Landings in previous seasons have been highest in San Diego, followed by Santa Barbara/Ventura, and then Los Angeles/Orange Counties. The lobster fishery was valued at $5.91 million in 2004, up from $5.02 million in 2003. California ex-vessel prices for spiny lobster consistently range from $6.50 to $8.00/lb. The spiny lobster catch is primarily exported to Asian markets, so prices depend on the strength of these overseas markets. In recent years, there has been an effort to develop a domestic market. However, results have been limited because of the common availability of American lobsters (*Homarus americanus*) at a much lower cost.

There has been a commercial fishery for California spiny lobster in southern California since the late 1800s, and commercial landings have been recorded since 1916 (fig. 7). Fishermen use baited traps that are individually set and buoyed to capture lobster alive. There is also a recreational fishery, where both skin and scuba divers are allowed to capture lobster using only their hands. Up to five baited hoop nets may also be used to take lobster recreationally, and this method of take is growing more popular. Commercial and recreational fishermen take lobster in shallow, coastal rocky areas from Point Conception south to the Mexican border and at offshore banks and islands. Lobster season runs from early October through mid-March, and the majority of the landings occur in the first few months of the season.

Since the 1950s, there have been several major regulation changes to better manage the fishery. In 1955, a minimum-size limit of 8.26 cm (3.25 in.) carapace length was established for both recreational and commercial fishers. Since the 1976–77 season, commercial fishermen have been required to use rectangular escape ports (6.05 cm x 29.2 cm) (2.38 in. x 11.5 in.) on traps to decrease the retention of undersized lobster. This management tool, along with warming ocean conditions following the regime shift in 1977, helped reverse the long downward trend in landings from the late 1950s to the 1970s (fig. 3).

A restricted access program for the commercial take of spiny lobster was initiated in the 1996–97 season after a two-year moratorium on permits. Although the number of active participants varies little from season to season, the number of lobster operator permits declines every year. Since 2000, six to nine permits have not been renewed annually. In the prior season (2003–04), a total of 228 permits were renewed, with only 154 actively fishing lobster. Prior to 2003, a small number (three or less) of new permits were issued via a lottery to qualified lobster crewmembers. In February 2003, the Commission repealed the permit lottery and the capacity goal of 225 fishermen. This was done in anticipation of CDFG conducting a formal review of the fishery, which did not take place as planned. Consequently, the industry went back to the Commission in 2004 and requested that it be allowed to move forward on a regulatory change that would allow qualifying lobster permits to be transferred. CDFG and the industry are working together to come up with a transferability program that will not cause a large increase in trap effort.

A logbook for the commercial fishery has been required since 1973. The logbook contains catch and effort information, such as the number of legal-sized lobster taken, the number of small lobsters released, the number, depths, and locations of traps used, and the number of nights the traps were fished. Logbook compliance has remained high (90% and greater) so CDFG has confidence in the effort estimates derived from the logbooks. The total number of traps pulled in the 2003–04 lobster season was estimated at over 900,000. This number has steadily increased since the 1981–82 season when about 500,000 traps were pulled. Since the number of trap pulls has not been accompanied by a corresponding increase in catch, CDFG wants to adopt a conservative transferability program.

Currently, there are no limits on the amount of lobster commercial fishers can land nor on the number of traps they can use. Fishers set their traps along depth contours in shallow water at the beginning of the season and move them farther from shore (>30.5 m, >100 ft) as the lobsters migrate offshore. This offshore-nearshore migration is stimulated primarily by water temperature. Typically, fishers set 100-300 traps, but those with larger boats or a crewmember may set more.

The bag limit for recreational fishers is seven lobsters a day, down from ten a day in 1971. There are no other limits or reporting requirements, such as punch cards, to track the recreational take of spiny lobster. Department biologists are actively collaborating with Sea Grant and graduate students to develop methods of sampling and assessing the recreational take of lobster.

The commercial lobster industry has shown considerable concern about how the recently established Marine Protected Areas (MPAs) in the Channel Islands National Marine Sanctuary will affect their fishery. Department landings data, however, showed an increased catch of nearly 13% at the Channel Islands in the period after the MPAs were implemented when compared to the five previous seasons. This trend does not indicate that the MPAs are necessarily benefiting fishermen, but it does show that the immediate losses forecasted by the industry did not occur.

In 2003, studies were initiated by students from the Donald Bren School of Environmental Science & Management (University of California Santa Barbara) to develop a long-term monitoring program of the lobster resource in collaboration with stakeholders. Lobster fishers and Bren students are now collecting data together to characterize the lobster resource and its associated commercial fishery inside and out of MPAs. Another long-term goal is to provide assessment data for a fishery management plan for California's spiny lobster.

Spot and Ridgeback Prawn

Preliminary 2004 spot prawn (*Pandalus platycerous*) landings were 101 t, a 25 % increase from 2003 (76 t) (fig. 8). Until 2002, spot prawn were harvested by trawl and trap gear. In 2003, the use of trawl gear for the take of spot prawn was outlawed because of the bycatch of rockfish, particularly bocaccio, an overfished species.

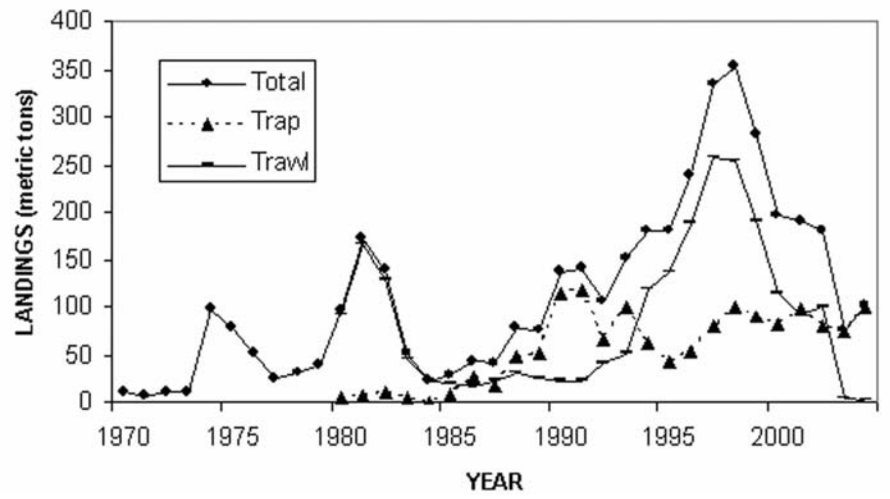

Figure 8. California commercial landings of spot prawn (*Pandalus platycerous*) using trawl and trap gear from 1970–2004.

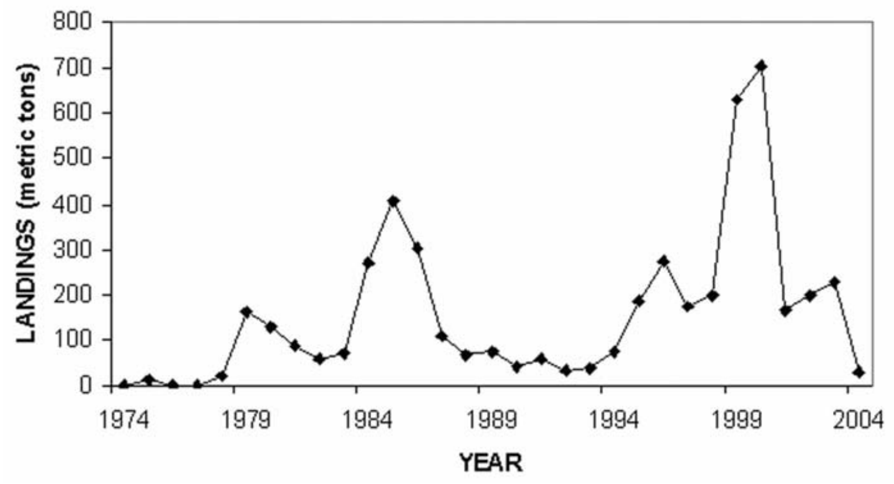

Figure 9. California commercial landings of ridgeback prawn (*Sicyonia ingentis*) from 1974–2004.

Consequently, 2003 spot prawn landings were the lowest since 1987 when trapping was just getting underway in southern California.

Spot prawn are currently caught only with trap gear. The traps are made of wire or plastic mesh of at least 2.22 × 2.22 cm (7/8 × 7/8 in.). The baited traps are fished in strings at depths of 100–167 m (600–1,000 ft.). A two-tiered restricted access trap vessel permit program was initiated in 2002. In 2004, 16 of the 17 Tier 1 trap vessels fished spot prawn from Santa Cruz south to the Mexican border. Tier 1 permittees may use no more than 500 traps unless fishing in state waters north of Pt. Arguello where they are only allowed the use of 300 traps. All three of the Tier 2 vessel permittees also made landings, but are limited to an annual harvest quota of just over 2 t (5,000 lbs.) and may use no more than 150 traps. A 0.023 t (50 lb) allowance of spot prawn while trawling for ridgeback prawn is still legal, but spot prawn may not be landed as bycatch when trawling for pink shrimp. Eight ridgeback trawl vessels landed 1.4 t of spot prawn in 2004 caught as bycatch.

Almost all spot prawn harvested is sold live, with prices ranging from $10.00 to $13.50/individual. Fresh dead spot prawn generally sells for half the price of live. Most trap permittees have invested in live tanks and chillers on their vessels to keep the prawns in top condition for the live market.

The trap fishery in southern California (south of Pt. Arguello) is closed from 1 November to 31 January to protect gravid females. North of Point Arguello, the spot prawn trap season is closed from 1 May to 31 July, an accommodation to prevent serious fishing gear conflicts in the Monterey Bay area.

When the use of trawl gear for the take of spot prawn was prohibited, the Commission directed CDFG to develop a conversion program for the trawl fleet. A conversion program went into effect at the end of 2004, which allowed the owners of 11 former trawl vessels to purchase Tier 3 spot prawn trap vessel permits. The fee for these permits is $1,000, and they are non-transferable, whereas the Tier 1 vessel permit fee is $250, and they were transferable on 1 April 2005. Tier 2 permits are non-transferable and have a fee of $250.

Ridgeback prawn (*Sicyonia ingentis*) landings totaled 28 t in 2004, the lowest harvest since 1978 (fig. 9) when the fishery was just starting to expand. Ridgeback prawn are only taken with trawl gear, almost entirely in the Santa Barbara Channel. Ridgeback prawns are usually fished in 50–100 m (300–600 ft.) of water. Ninety-seven percent of the landings in the past two years were made in the ports of Santa Barbara and Ventura. Thirty boats landed ridgeback prawn in 2002, 25 in 2003, and only 14 in 2004. The closed season is between 1 June and 30 September, the spawning period for ridgeback shrimp.

In 2003, when ridgeback prawn were more abundant, the average price was only $1.35/lb. The scarcity of ridgeback prawn in 2004 resulted in an average ex-vessel price of $2.20/lb. Most of the catch is frozen whole for export and domestic markets.

Ridgeback prawn trawl logs, required since 1986, show that the catch per unit effort (CPUE) in lbs/tow hour varies with the abundance of prawn. CPUE increased from a low of 32 lbs/tow hour in 1992 (34 t harvest) to a high of 213 lbs/tow hour in 1999 (632 t harvest). CPUE averaged 72 lbs/tow hour in the three years prior to 2004, when it dropped to 32 lbs/tow hour. No biomass estimates or maximum sustainable yield calculations exist for ridgeback prawn. However, the landing figures reflect the species' wide fluctuation in availability.

Groundfish

Commercial Fishery Landings. California's commercial groundfish harvest for 2004 was 12,269 t (tab. 3). Total landings increased 16% (1,705 t) from 2003, although they have decreased by 50% (12,403 t) from 1994. The 2004 ex-vessel value for all groundfish was $13.7 million, a decrease of $1.1 million, or 7.4%, from 2003 revenues ($14.8 million).

In 2004, 88% of the groundfish were landed with bottom and mid-water trawl gear, a slight increase over 2003 (85%). Line gear was second at 9%, a slight decrease from 2003 (11%). Trap gear accounted for 2.5% of 2004 landings, while the gill and trammel net remained at less than 1%, a decline from 5% in 1993.

The 2004 groundfish harvest was dominated by Pacific whiting, *Merluccius productus*, (4,742 t), Dover sole, *Microstomus pacificus*, (2,419 t), rockfishes, *Sebastes* spp., (1,758 t), and sablefish, *Anoplopoma fimbria*, (1,429 t) (tab. 3). Dover sole, thornyheads (*Sebastolobus alascanus* and *S. altivelis*) and sablefish (the DTS complex) landings decreased 29% from 2003, with decreases in all three fisheries, most notably in the thornyhead fishery where landings decreased by 57%. However, chilipepper (*S. goodie*) landings increased 261%. Pacific whiting landings also increased from the previous year, with landings increasing by 172%. Widow rockfish (*S. entomelas*) and lingcod (*Ophiodon elongates*) landings also increased 160% and 19%, respectively. Another large contributor to the groundfish landings was English sole (*Parophrys vetulus*), with a 134% increase. These fisheries were offset, however, by the decreases in the DTS complex—sanddabs, rex sole (*Glyptocephalus zachirus*), and grenadier (*Macrouridae*, sp).

TABLE 3
California 2004 Commercial Groundfish Landings (metric tons)

	2004	2003	% change since 2003	1994	% change since 1994
Flatfishes	3,909	4,767	–18%	6,912	–43%
Dover sole	2,419	3,256	–26%	4,487	–46%
English sole	307	131	134%	460	–33%
Petrale sole	489	380	29%	548	–11%
Rex sole	211	258	–18%	570	–63%
Sanddabs	354	605	–41%	680	–48%
Other flatfishes	129	137	–6%	167	–23%
Rockfishes	1,758	1,984	–11%	10,722	–84%
Thornyheads	550	1,281	–57%	3,316	–83%
Widow	13	5	160%	924	–99%
Chilipepper	65	18	261%	1,847	–96%
Bocaccio	6	1	500%	973	–99%
Canary	1	1	0%	209	–100%
Darkblotched	47	12	292%	292	–84%
Splitnose	161	151	7%	334	–52%
Other rockfishes	915	515	78%	2,827	–68%
Roundfishes	6,423	3,631	77%	6,932	–7%
Lingcod	62	52	19%	564	–89%
Sablefish	1,429	1,629	–12%	2,184	–35%
Pacific whiting	4,742	1,741	172%	3,613	31%
Grenadier	139	163	–15%	529	–74%
Cabezon	49	40	23%	40	23%
Other roundfishes	2	6	–67%	2	0%
Other groundfishes	179	182	–2%	106	69%
Total	12,269	10,564	16%	24,672	–50%

Recreational Fishery Catches. The new recreational sampling program, the California Recreational Fisheries Survey (CRFS), was implemented 1 January 2004. Estimates from this new program indicated that California anglers, regardless of trip type, spent an estimated 4.7 million angler-days fishing and caught about 1,100 t of groundfish (tab. 4). About 233,000 angler-days targeted rockfish and lingcod, resulting in a take of 659 t groundfish or about 60% of the total groundfish from all trips. Another 144 t of groundfish were taken during "other" trips (those trips that did not fall into any of the other trip type categories) and included trips that targeted California scorpionfish (*Scorpaena guttata*) and Pacific sanddab (*Citharichthys sordidus*). In addition,

TABLE 4
Statewide California Estimates for Examined and Discarded Dead Catch by Weight (metric tons) of Groundfish for Specified Trip Type Categories and Groundfish Groups and Estimates of Recreational Effort (angler-days) by Trip Type Category

Groundfish Group	Rockfish, Lingcod	Other[1]	Anything	HMS, Coastal Migratory, Bass[2]	Salmon	Bay Species, Halibut[3]	Miscellaneous[4]	Total Trips
Leopard Shark/Spiny Dogfish	0.2	0.1	4.7	8.2	0.2	8	0.1	21.4
Minor Nearshore Rockfish[5]	318.7	60.8	44.6	25.4	23.4	7.1	0.5	480.6
Rockfish Species of Concern[6]	42	5.7	22	13.9	0.4	1.9	0	85.9
Other Shelf/Slope Rockfish	196.8	12.5	46.8	35.7	4.8	3.9	0.1	300.6
Lingcod	71.8	22.6	8.4	7.8	9.5	1.7	0.6	122.4
Cabezon/Greenling	26.1	3.9	5.1	5	2.9	0.6	0.3	43.8
Pacific Sanddab, Soles, Thornyheads	3.2	38.6	3.5	1.1	0.6	1	0.1	48
Starry Flounder	0.1	0	0.1	0.1	0.4	1.2	0.1	2
Pacific Whiting, Sablefish	0	0	0	0	0.8	0	0	0.8
Total Estimated Groundfish Catch	659	144.2	135	97.1	43	25.4	1.7	1105.5
Total Angler-Days	233,165	153,761	2,010,261	1,243,872	271,560	403,219	415,161	4,730,999

[1] Other trip types include any target species not covered under the specified groups and include targeted California scorpionfish and Pacific sanddab trips.
[2] The Highly Migratory Species, Coastal Migratory, Bass trip type category includes the tuna/sharks/billfish, yellowtail, white seabass, and bass/barracuda/bonita trip types
[3] The Bay Species, Halibut trip type category includes the sturgeon, striped bass, and halibut trip types.
[4] The Miscellaneous trip type category includes the croakers, perches, corbina, and smelt trip types.
[5] The Minor Nearshore Rockfish group includes black rockfish.
[6] The Rockfish Species of Concern group includes the following rockfishes: bocaccio, canary, cowcod, widow, and yelloweye.

135 t of groundfish, or 12% of the total from all trips, was taken by anglers that were fishing for any finfish species that was available. Much of the remaining groundfish was taken by anglers targeting highly migratory species, coastal migratory species [yellowtail (*Seriola lalandi*), barracuda (*Sphyraena argentea*), white seabass (*Atractoscion nobilis*), Pacific bonito (*Sarda chiliensis*), basses—kelp bass (*Paralabrax clathratus*), barred sand bass (*P. nebulifer*)—,bay species (sturgeon (*Acipenser* spp.), and striped bass (*Morone saxatilis*)], California halibut (*Paralichthys californicus*), and salmon (*Oncorhynchus* spp.). In particular, the small amount of Pacific whiting was taken during trips targeting salmon while the landings of leopard shark (*Triakis semifasciata*) and starry flounder (*Platichthys stellatus*) were reported from trips targeting bay species and California halibut. In addition, leopard shark was taken during trips that targeted highly migratory and coastal migratory species.

2004 Groundfish Fishery Management Highlights. In 2004, Pacific whiting was removed from the overfished status. Originally declared overfished in 2002, a new assessment was provided to the PFMC's Stock Assessment Review (STAR) Panel and Scientific and Statistical Committee (SSC) for review. In 2003, the STAR panel and SSC considered two assessment models, both of which indicated the presence of a strong 1999 year class and that the estimated spawning stock biomass had reached its rebuilding threshold. Following recommendations from both the STAR panel and the SSC, NOAA Fisheries declared the West Coast stock of Pacific whiting as officially rebuilt and thus no longer considered an overfished species. Using these new assessment results, the PFMC set new harvest guidelines with an acceptable biological catch of 514,441 mt for the entire stock.

Early in 2004, the PFMC adopted rebuilding plans for bocaccio (*S. paucispinis*), cowcod (*S. levis*), widow and yelloweye (*S. ruberrimus*) rockfishes under the Pacific Coast Groundfish Fishery Management Plan Amendment 16-3. It also mandated the use of the Cowcod Conservation Areas (CCA) as a primary cowcod rebuilding strategy. Finally, the PFMC asked the SSC to revise the Terms of Reference used to evaluate rebuilding plans for overfished groundfish stocks.

At the June 2004 PFMC meeting, NOAA Fisheries reported successful implementation of the Vessel Monitoring System (VMS) program and the associated telephone declaration system for those vessels with federal limited-entry groundfish permits. Nearly 300 VMS units are now in operation.

During 2004, NOAA Fisheries and the PFMC worked on developing an environmental impact statement (EIS) that proposed amending the Pacific Coast Groundfish FMP (FMP) to address essential fish habitat (EFH) for groundfish. A major management tool that the PFMC also considered in 2004, and continues to consider in 2005, is the creation of a dedicated access privilege [or individual quota (IQ)] system for the Pacific Coast groundfish limited-entry trawl fishery. A trawl IQ program would change harvest management in the trawl fishery from a cumulative two-month trip limit system to an individual annual quota system.

In-season Adjustments. In-season changes to the commercial and recreational management specifications

TABLE 5
California Commercial Landings (metric tons) and Ex-vessel Values of Highly Migratory Species in 2004 and 2003

	Landings (t)			Ex-vessel Value (US$)		
	2004	2003	% change from 2003	2004	2003	% change from 2003
Tunas						
Albacore	1,350	1,720	–22	2,449,097	2,609,146	–6
Yellowfin	478	465	3	447,496	449,708	<–1
Skipjack	304	349	–13	109,199	159,938	–32
Bluefin	37	36	3	53,487	74,552	–28
Bigeye	21	34	–38	147,696	262,766	–44
Billfishes						
Swordfish	817	1,472	–44	4,824,694	7,850,629	–39
Striped Marlin[a]	—	—	—	—	—	—
Roundfish						
Dorado	1	6	–83	5,638	8,200	–31
Sharks						
Common Thresher	67	177	–62	195,417	486,856	–60
Bigeye Thresher	3	3	0	4,139	3,782	9
Pelagic Thresher	1	2	–50	2,500	2,814	–11
Shortfin Mako	37	48	–23	97,071	115,504	–16
Blue[b]	—	—	—	—	—	—
Total	3,116	4,321	–28	8,336,430	12,023,890	–31

[a] Commercial landings are prohibited in California.
[b] Reported landings less than 50 kilograms.

were implemented throughout 2004, as in past years, and are highlighted by the following:

Commercial Fishery

- A revised trawl bycatch model updated with a new year of at-sea observations and a new primary sablefish fixed-gear bycatch model were adopted for use in management decision making for in-season adjustments in 2004.
- In the spring, the PFMC recommended increased trip limits for Dover sole, thornyheads, and sablefish (the DTS complex) and petrale sole, arrowtooth flounder (*Atheresthes stomias*), and other flatfishes based on the updated trawl bycatch model projections. However, in the summer, the PFMC recommended adjusting cumulative limits for the DTS complex and petrale sole because landings were tracking ahead of projections.
- The PFMC's Groundfish Management Team identified the Cordell Bank as an area of particularly high catch of canary rockfish (*Sebastes pinniger*), an overfished rockfish species, and the PFMC and CDFG adopted closure of Cordell Bank to commercial and recreational fishing.
- The PFMC recommended adjusting regulatory requirements on trawl gear use to provide more opportunities to harvest target species with minimal effects to overfished species.
- During the summer, changes in landings allowances of incidental catches in the limited-entry trawl- and limited-entry fixed-gear fisheries were made for the remainder of the year.
- Darkblotched rockfish (*S. crameri*), as well as the deepwater slope species, and canary rockfish trip limits were increased, but later in the year, the PFMC recommended moving the trawl Rockfish Conservation Area (RCA) boundaries seaward to bring the total mortality of darkblotched rockfish close to zero. This latter action was taken due to higher-than-expected catches of darkblotched rockfish.

Recreational Fishery

- Various more restrictive in-season adjustments were also recommended in April 2004 to achieve PFMC harvest objectives for lingcod and canary rockfish.
- Upon Commission recommendation, the PFMC recommended that NOAA Fisheries change recreational bag limits for the rockfish/cabezon/greenlings complex north of 40°10'N latitude (near Cape Mendocino) to match regulations south of 40°10'N latitude.
- A closure of the Cordell Bank was implemented in the final rule for 2004 groundfish fisheries.
- The PFMC recommended in March 2005 that the Commission adopt an increase in the lingcod minimum-size limit from 24 inches to 30 inches and a reduction of the bag limit from two fish to one fish.

Highly Migratory Species

Albacore. Albacore (*Thunnus alalunga*) is the leading highly migratory species (HMS) caught in both commercial and recreational fisheries in California (Tabs. 5, 6). In 2004, commercial landings totaled 1,350 t, down 22% from 2003 (1,720 t). Ex-vessel revenues also decreased 6% ($2.4 million) from 2003 ($2.6 million);

TABLE 6
California Recreational Commercial Passenger Fishing Vessel Landings (number of fish) of Highly Migratory Species in 2004 and 2003

	Landings (number of fish)		
	2004	2003	% change from 2003
Tunas			
Albacore	181,620	249,651	–27
Yellowfin	62,189	29,947	108
Skipjack	4,324	32,249	–87
Bluefin	3,356	22,334	–85
Bigeye	434	60	86
Billfishes			
Swordfish	2	2	0
Striped marlin	4	4	0
Roundfish			
Dorado	7,731	3,211	141
Sharks			
Common thresher	18	26	–31
Bigeye thresher	1	0	100
Pelegic thresher	1	3	–67
Shortfin mako	301	113	166
Blue	6	47	–87
Total	259,988	337,647	–23

however, the average price per ton increased 16% from $1,249 in 2003 to $1,493 in 2004. Almost all (99%) of the albacore landed in California was landed using surface hook-and-line gears; some incidental take occurred in gillnets and purse seine gears. Exports of fresh frozen albacore from California went to Ecuador and Spain for canning. This decline in landings doesn't necessarily reflect a decline in the albacore population. Commercial albacore landings have varied dramatically over the last decade, ranging from 5,585 t in 1999 to 833 t in 1995, significantly lower than the highs in the 1950s and 1960s when landings were routinely over 27,000 t. This decline is attributed to a shift in fishing effort by the California-based fleet into waters off Oregon and Washington where albacore have been more available. Commercial landings of albacore in Oregon and Washington in 2004 were 4,807 t and 6,157 t, respectively.

Commercial Passenger Fishing Vessel (CPFV) logbook data indicate that recreational anglers landed 181,620 albacore, down 27% from 2003 (249,651) and down 42% from the record high of 312,776 in 2002. Eighty-nine percent of the reported catch occurred south of the U.S.-México border. According to CRFS data, the average weight per fish in 2004 was 7.1 kg, resulting in an estimated total landed weight of 1,290 t.

Stock status of albacore is reviewed at one to two year intervals by the North Pacific Albacore Workshop (members: United States, Japan, Canada, and Taiwan). Presently, the stock is healthy and not overfished, although stock and catches are increasing throughout the north Pacific. No quotas are being contemplated, and no regional harvest guidelines are recommended at this time.

Yellowfin Tuna. Commercial landings of yellowfin (*Thunnus albacares*) totaled 478 t, up 3% from 2003 (465 t). The ex-vessel revenues decreased 1% ($447,496) from 2003 ($449,708). The average price-per-ton also decreased 3% from $796 in 2003 to $770 in 2004. California's coastal purse seine fleet caught 99% of the yellowfin landed in California. Exports of fresh frozen yellowfin tuna from California went mainly to México for processing. The annual landing trend has been declining since 1974, when more than 111,600 t of yellowfin was landed in California. The decline in commercial landings can be attributed to the relocation of large cannery operations overseas. Currently there are no canneries operating in California.

CPFV logbook data indicate the recreational anglers landed 62,189 yellowfin, twice the 29,947 fish reported in 2003. The increase in the CPFV landings can be attributed to an abundance of small yellowfin (<600 mm fork length) in coastal waters in the late summer and early fall. However, the 2004 catch is significantly lower than the high of 116,000 fish in 1983. While CPFVs from San Pedro to San Diego recorded catches of yellowfin, 87% of the 2004 catch was harvested south of the U.S.-México border. According to CRFS data, the average weight per fish in 2004 was 3.8 kg, resulting in an estimated total landed weight of 236 t.

The yellowfin stock appears to be below, but near, maximum sustainable yield (MSY), with fishing mortality higher than that recommended by the HMS FMP. The Inter-American Tropical Tuna Commission (IATTC) conducts stock assessments annually, and the recommended quota is usually between 250,000 and 300,000 t for the Eastern Pacific Ocean (EPO). In view of the small share (about 1%) of the total yellowfin catch made by West Coast fishers, and the productivity of the stock, no regional harvest guidelines were recommended at this time.

Skipjack Tuna. Commercial landings of skipjack (*Katsuwonus pelamis*) totaled 304 t, down 13% from 2003 (349 t). The ex-vessel revenues decreased 32% ($109,199) from 2003 ($159,938), and the average price per ton decreased by 22% from $459 in 2003 to $359 in 2004. Purse seine vessels caught 99% of the skipjack landed in California. Exports of fresh frozen skipjack went to México and Spain for processing and canning. Skipjack landings have declined over the past 24 years following the high of 78,926 t in 1980. The decline in commercial landings in California is attributed to the relocation of large cannery operations to overseas locations and the reflagging of U.S. vessels. Currently, there are no canneries operating in California. Almost all commercial skipjack landings in California are caught south of the U.S.-México border.

CPFV logbook data indicates recreational anglers landed 4,324 fish, down 87% from 2003 (32,249 fish). According to CRFS data, the average weight per fish in 2004 was 2.8 kg, resulting in an estimated total landed weight of 12 t. The decrease in landings can be attributed to a shift of skipjack from southern California's coastal waters in 2003 to waters beyond reach of the local CPFV fleet in 2004.

The eastern Pacific skipjack stock is assessed annually by the IATTC and appears to be very productive. No upper limit to the catch is evident, and no MSY has been established. In view of the small share (about 3%) of total catch made by West Coast fishers, and the productivity of the stock, no regional harvest guidelines were recommended.

Bluefin Tuna. Commercial landings of bluefin (*Thunnus thynnus*) totaled 37 t, up 3% from 2003 (36 t). The ex-vessel revenues decreased 28% ($53,487) from 2003 ($74,552); however, the average price per ton increased 63% from $1,708 in 2003 to $2,776 in 2004. Purse seine vessels operating in the Southern California Bight (SCB) caught 75% of the bluefin landed in California, and the drift gillnet fleet accounted for 25% of the reported landings. Exports of fresh frozen bluefin tuna from California went to Japan. Historically, landings peaked at more than 17,000 t in 1966. Since then, landings have been variable but declining due to a decrease in the availability of bluefin in the EPO and a decrease in the number of boats which direct their effort at them.

CPFV logbooks data indicate that recreational anglers landed 3,356 bluefin, down 85% from 22,334 fish landed in 2003. According to CRFS data, the average weight per fish in 2004 was 8.8 kg, resulting in an estimated total landed weight of 21 t. Of the bluefin landed by CPFV passengers, 86% was caught south of the U.S.-México border.

The IATTC reviews the status of the northern bluefin tuna stock occasionally. Evidence of overfishing or persisting decline in the stock is lacking. West Coast fishers account for about 10% of the total catch of the stock, harvesting mainly juveniles that migrate irregularly to the eastern Pacific. In view of the limited effect West Coast fisheries have on the spawning stock and the lack of international agreement on the need to control fishing mortality, no regional harvest guidelines were recommended.

Bigeye Tuna. Commercial landings of bigeye tuna (*Thunnus obesus*) totaled 21 t, down 38% from 34 t landed in 2003. The ex-vessel revenues also decreased 28% ($147,696) from 2003 ($262,766). Overall, bigeye commanded the highest average price per ton of all tunas landed in California; however, the average price per ton dropped 7% from $6,341 in 2003 to $5,902 in 2004. The offshore longline fishery landed 100% of the bigeye in California. Exports of fresh frozen bigeye from California went to Canada.

CPFV logbook data indicate that recreational anglers landed 434 bigeye tuna, a seven-fold increase from 60 fish landed in 2003. Bigeye caught south of the U.S.-México border accounted for 89% of the landed fish. There is no CRFS estimate for an average weight in 2004.

In June of 2004, NOAA Fisheries declared bigeye tuna in the western and central Pacific overfished. By November, NOAA Fisheries implemented a final rule to close the U.S. longline fishery for bigeye when the landings reached 150 t. The Fishery closed 13 December 2004.

Billfishes

Swordfish. Commercial landings of swordfish (*Xiphias gladius*) totaled 817 t, down 44% from 1,472 t landed in 2003. The ex-vessel revenues also decreased 39% ($4.8 million) from 2003 ($7.9 million); however, the average price per ton increased 11% from $4,388 in 2003 to $4,859 in 2004. Most swordfish landed in California support domestic seafood restaurant businesses. In the late 1970s, the swordfish fishery transformed from primarily a harpoon fishery to a drift-net fishery, and landings soared to a historical high of 2,357 t by 1985. Since then, annual landings have averaged more than 1,400 t.

Recreational anglers fishing from private vessels occasionally catch swordfish in southern California, but catch estimates are indeterminate due to a low number of sampler contacts with fishers. CPFV logbook data indicate only two fish landed in 2004 and 2003, indicating this mode of fishing is an insignificant component of the fishery.

Striped Marlin. The HMS FMP prohibits the commercial take or sale of striped marlin (*Tetraptarus audax*) to provide for and maximize recreational fishing opportunities. Marlin is caught as bycatch in the drift gillnet fishery for swordfish, resulting in regulatory discard.

Recreational anglers fishing from private vessels catch the majority of the marlin in southern California, but catch estimates are indeterminate due to a low number of sampler contacts with fishers. CPFV logbook data indicate only four fish landed in 2004 and 2003, suggesting that this mode of fishing is an insignificant component of the fishery.

Roundfish

Dorado (Dolphinfish). Commercial landings of dorado (*Coryphaena hippurus*) totaled 1 t, a decrease from 6 t landed in 2003. The ex-vessel revenues also decreased 31% ($5,638) from 2003 ($8,200); however, the price per ton increased three-fold from $1,131 in 2003 to $4,185 in 2004. High-seas longline vessels land the majority (62%) of dorado, followed by hook-and-line

(32%) and troll (6%) gears. Historically, dorado landings have been a relatively small component of the HMS management unit, and they vary from year to year, primarily depending on cyclic intrusions of warm water into the SCB. Dorado landings support local seafood restaurants in southern California when available to the commercial fleet.

CPFV logbook data indicate that recreational anglers landed 7,731 dorado, a two-fold increase from 3,211 fish landed in 2003. There is no CRFS estimate for an average catch weight in 2004. Dorado caught south of the U.S.-México border accounted for 91% of the landings.

Sharks

Common Thresher. Commercial landings of common thresher (*Alopias vulpinus*) totaled 67 t, down 62% from 177 t landed in 2003. The ex-vessel revenues also decreased 60% ($195,417) from 2003 ($486,856); however, the average price per ton increased 6% from $2,266 in 2003 to $2,400 in 2004. The common thresher is the leading shark landed in California where it is harvested primarily by drift gillnets (58%), followed by set gillnets (39%), and other assorted gears (3%) throughout the year. The thresher shark fishery emerged with the development of the drift gillnet fishery in the mid 1970s and supports the domestic seafood restaurant industry. Bigeye and pelagic threshers are also landed in California, but are a relatively minor component of the fishery. Because basic population dynamic parameters for these shark species are unknown, they are managed with a precautionary harvest guideline of 340 t.

CPFV logbooks data indicate that recreational anglers landed 18 common threshers, down from 26 fish landed in 2003. Recreational anglers fishing from private vessels in the SCB commonly catch thresher sharks, but catch estimates are indeterminate due to a low number of sampler contacts with fishers.

Shortfin Mako. Commercial landings of shortfin mako (*Isurus oxyrinchus*) totaled 37 t, down 23% from 48 t landed in 2003. The ex-vessel revenues also decreased 16% ($97,071) from 2003 ($115,504); however, the average price per ton increased 10% from $1,976 in 2003 to $2,168 in 2004. Mako is the second-most-common shark landed in California, where it is harvested by the drift-gillnet (42%) fishery targeting swordfish, followed by set-gillnet (38%), hook-and-line (11%), set longline (5%), and assorted gears. Landings occur throughout the year with the highest monthly landing weights occurring May through September. Because basic population dynamic parameters for this species of shark are unknown, it is managed with a precautionary harvest guideline of 150 t.

CPFV logbook data indicate that recreational anglers landed 301 makos, up almost three-fold from 113 fish landed in 2003. Recreational anglers fishing from private vessels in the SCB commonly catch makos, but catch estimates are indeterminate due to a low number of sampler contacts with fishers.

Blue Shark. Commercial landings of blue shark (*Prionace glauca*) totaled 13 kg in 2004, a decrease from 49 kg in 2003. Over the past decade, landings have been minimal, averaging 5 t annually. Despite the low landings, this species is caught as bycatch in the drift-gillnet fishery and pelagic-longline fishery and discarded at sea. Survival rates of discarded blue sharks are unknown.

CPFV logbook data indicate that recreational anglers landed six sharks in 2004, down from 47 sharks in 2003. This species is not the target of the CPFV fleet.

2004 HMS Fishery Management Highlights. The PFMC and NOAA Fisheries completed the Highly Migratory Species Fishery Management Plan (HMS FMP) in March of 2004. The plan provides a management framework for HMS harvested within the EEZ and adjacent high-seas waters off the contiguous West Coast states. Adoption of the HMS FMP provided for implementation of new management and conservation tools, consolidation of existing state and federal tools, and international agreements for HMS. The new conservation and management tools include harvest control rules for common thresher and shortfin mako sharks, definition of prohibited and protected species, establishment of incidental HMS catch allowances, requirements for a new federal HMS vessel permit, requirements for logbook reporting and submissions, requirements for carrying fishery observers, and a summary of mandatory time and area closures.

Commercial fishing gears authorized for the harvest of HMS include: harpoons, surface hook-and-line gears, purse seines, drift gillnets, and longlines. Pelagic longline gear is prohibited inside the West Coast EEZ as is shallow-set longline gear in the adjacent high-seas areas to avoid gear interactions with endangered sea turtles and sea birds. Recreational gears authorized for harvest of HMS are hook-and-line, rod-and-reel, and spear.

There are two turtle conservation areas on the West Coast with seasonal drift gillnet restrictions. The Pacific Leatherback Conservation Area (PLCA), the largest of two conservation areas, spans the Eastern Pacific Ocean (EPO) north of Point Conception, California (34°27'N) to Oregon (45°N) and west to 129°W. Drift-gillnet fishing is prohibited annually within the PLCA from 15 August to 15 November. Another conservation area implemented to protect Pacific loggerhead turtles from drift-gillnet gear during a forecasted or occurring El Niño event is located south of Point Conception, California and west of 120°W from 1 January through 31 January and from 15 August through 31 August.

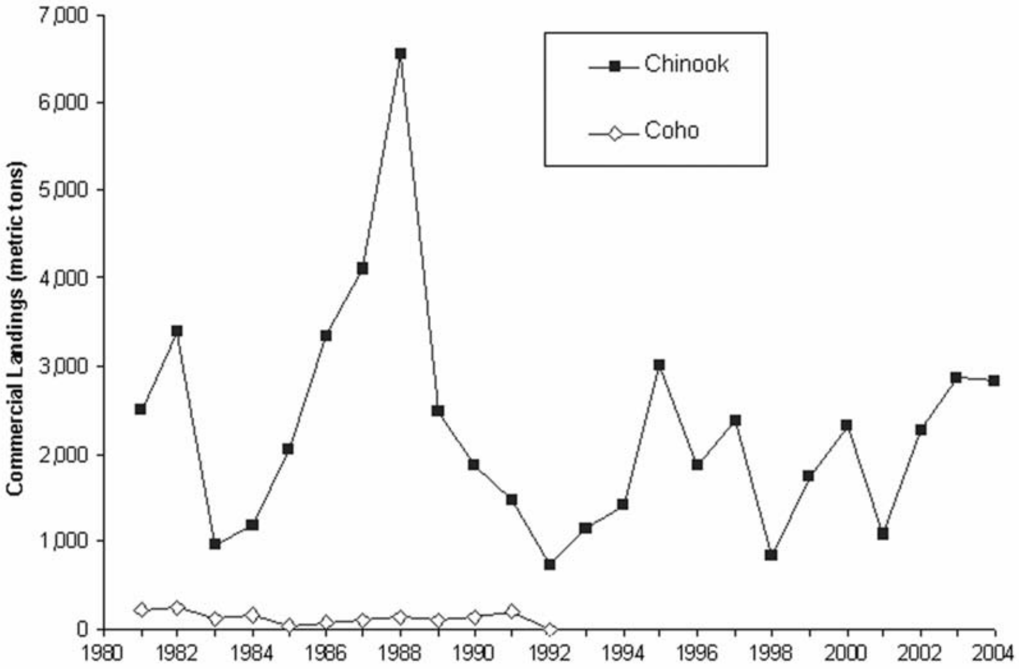

Figure 10. California commercial ocean salmon landings, 1981–2004.

Under the HMS FMP, stock status of tunas is determined by estimating the abundance (biomass) of the stock throughout its range and comparing the estimate of abundance with the adopted acceptable level of abundance. West Coast fisheries harvest a small fraction of the total catch taken by all nations in the north Pacific. Tuna catch by U.S. vessels based on the West Coast, as a percentage of the total catch for the stock, ranges from less than 1% for bigeye tuna to about 16% for albacore. In most cases, effective conservation of tunas requires international action.

Ocean Salmon

Commercial ocean salmon landings in 2004 were similar to 2003 landings. Approximately 500,800 dressed Chinook salmon (*Oncorhynchus tshawytcha*) were landed, weighing 2,824 metric tons in approximately 21,600 boat days (fig. 10). The value to the commercial fishing fleet was over $17.9 million with an average price of $2.87 per pound. Landings occurred primarily in the San Francisco and Fort Bragg port areas when open. This is partially due to a slight northern shift in the distribution of Chinook salmon, as well as an increase in the number of days open to fishing in Fort Bragg compared to the past few years. The 2004 ocean salmon seasons were slightly more restrictive than the 2003 seasons.

The recreational landings were more than double the 2003 landings. Landings totaled 220,200 Chinook salmon for 215,700 angler days (fig. 11). The average catch per angler day was 1.02 Chinook. There was a limit of two fish per angler in all California management areas. The take of coho salmon (*Oncorhynchus kisutch*) has been prohibited in the recreational fishery since 1996. In the California portion of the Klamath Management Zone (KMZ) (Horse Mountain to the California-Oregon border), 22,800 Chinook salmon were landed in 25,500 angler days with a minimum size of 20 inches total length (TL). South of Horse Mountain the size limit was 24 inches TL until 30 April and 20 inches TL for the remainder of the season. Barbless "circle" hooks were required when fishing by any means other than trolling north of Point Conception.

The 2004 ocean salmon regulations adopted by the PFMC were designed to do the following:

- provide commercial and recreational seasons south of Point Arena that were substantially the same as the 2000 and 2001 seasons in terms of timing and duration;
- allow an exploitation rate (marine and freshwater combined) of no more than 15% for Oregon coast natural coho;
- provide for at least 35,000 naturally spawning adult Klamath River fall Chinook with a minimum adult natural spawner escapement rate of 33%;
- meet the Klamath River fall Chinook allocation objectives of 50% (31,100 fish) of the allowable adult harvest for tribal subsistence and 50% for commercial fisheries, at least 15% (4,700 fish) of the non-tribal harvest for the Klamath River recreational fishery, and 14.1% (3,700 fish) of the ocean harvest for the KMZ (Horse Mountain, California to Humbug Mountain, Oregon) recreational fishery;

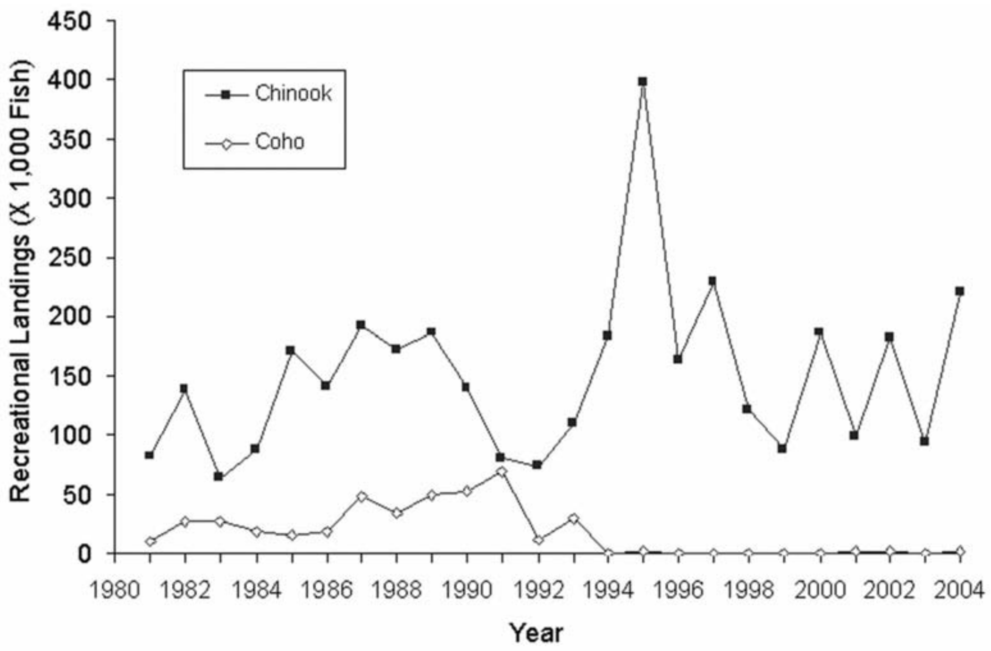

Figure 11. California recreational landings of ocean salmon, 1981–2004.

- limit the ocean harvest rate for age-4 Klamath River fall Chinook to no more than 16% to protect California coastal Chinook;
- provide for the escapement of 122,000 to 180,000 hatchery and natural adult Sacramento River fall Chinook; and
- prohibit the retention of coho salmon in California to protect central California coast coho.

For more complete information, see PFMC's Web site, <www.pcouncil.org>, where you will find the report "Review of the 2004 Ocean Salmon Fisheries," which was compiled by the PFMC Salmon Technical Team and PFMC staff.

Nearshore Live-Fish

Preliminary summaries of 2004 data indicated that commercial landings of California nearshore finfish totaled 247 t. Of that, 199 t were recorded as live landings and 48 t as dead landings. The ex-vessel value of total landings for 2004 was $2.2 million, of which $1.9 million was paid for live fish (fig. 12). Compared to 2003, this represents a 7% increase in total nearshore landings and a 10% increase in value. Live landings decreased by 2% compared to 2003, and there was no change in the total ex-vessel value. The proportion of live landings in the nearshore fishery declined to 81% compared to 87% in 2003 (fig. 13).

Management of the Fishery. The nearshore fishery, as defined in Section 1.90, Title 14 of the CCR, includes a select group of finfish: cabezon (*Scorpaenichthys marmoratus*), California scorpionfish (*Scorpaena guttata*), California sheephead (*Semicossyphus pulcher*), kelp and rock greenlings (*Hexagrammos decagrammus* and *H. lagocephalus*), monkeyface eel (*Cebidichthys violaceus*), and the following rockfishes (*Sebastes* spp.): black (*S. melanops*), black-and-yellow (*S. chrysomelas*), blue (*S. mystinus*), brown (*S. auriculatus*), calico (*S. dallii*), China (*S. nebulosus*), copper (*S. caurinus*), gopher (*S. carnatus*), grass (*S. rastrelliger*), kelp (*S. atrovirens*), olive (*S. serranoides*), quillback (*S. maliger*), and treefish (*S. serriceps*). The 19 species are primarily found in association with kelp beds or rocky reefs in waters less than 20 fathoms. Most are territorial, slow-growing, and long-lived, making them vulnerable to overfishing even at low exploitation rates. These species are commonly captured in the nearshore live-fish fishery, and they are managed by the state under the Nearshore Fishery Management Plan (NFMP). All except California sheephead, monkeyface eel, and rock greenling are also included in the PFMC fishery management plan for Pacific coast groundfish.

History and Fishing Operations. The nearshore live-fish fishery began in the mid-1980s. Initially, the fishery supplied live fish for the California Asian community. The live-fish market has since expanded and now supplies markets nationally and, in some cases, internationally. Before the market for live fish developed, the wholesale value (ex-vessel value) for rockfishes, cabezon, California sheephead, and greenlings was low. An increase in consumer demand for a premium quality product caused landings of live fish to increase. Because the ex-vessel price for live fish is usually higher than the price for dead fish, the overall value of the fishery increased dramatically. In 1989, cabezon was primarily landed dead and the average ex-vessel price was less than

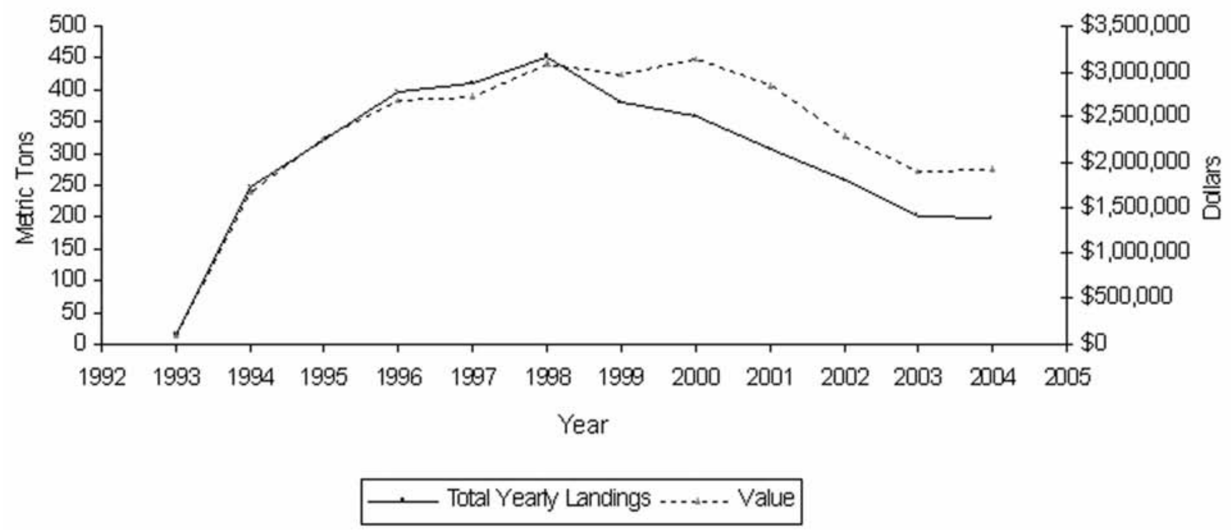

Figure 12. California nearshore live-fish landings and ex-vessel value, 1993–2004.

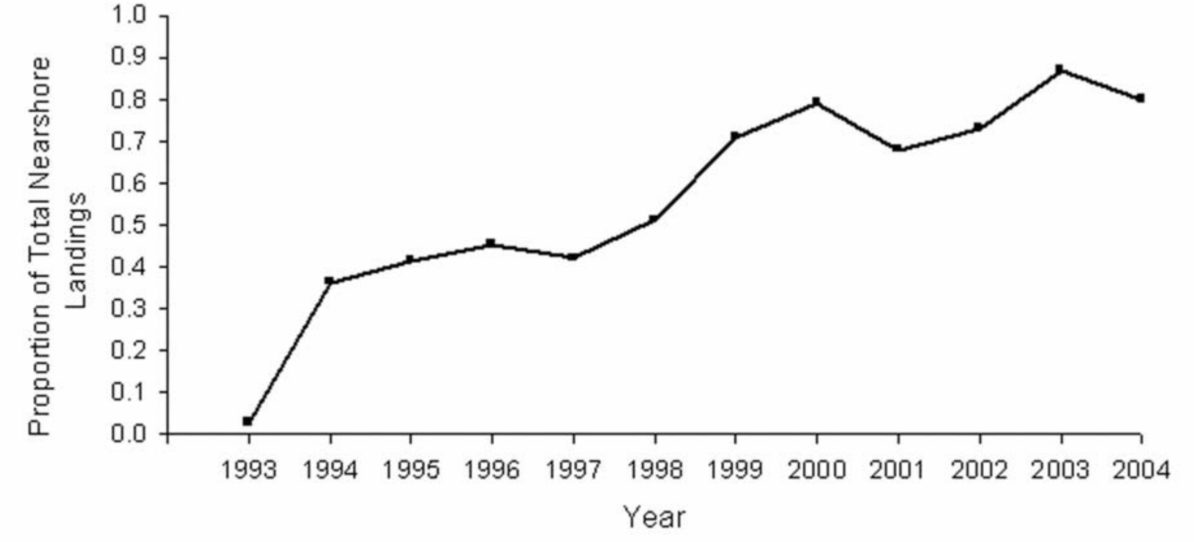

Figure 13. Proportion of fish landed live in the nearshore fishery, 1993–2004.

50 cents per pound. In 2004, the average ex-vessel price for dead cabezon was $2.40 per pound while the live cabezon price was $4.74 per pound (down slightly from $4.81 in 2003). Prices vary widely depending on port region, species, size, season, and marketability of fish. In 2004, ex-vessel prices for live landings of the 19 nearshore species ranged as high as $10.50 per pound.

Primary gear types used to capture nearshore fish include various hook-and-line methods and trap gear. Hook-and-line gear includes rod-and-reel, vertical longlines, horizontal longlines, and weighted "stick gear." Vessels using hook-and-line gear are limited to 150 hooks per vessel and not more than 15 hooks per line. In addition, no more than 50 finfish traps may be used in state waters along the mainland shore. Most hook-and-line and trap vessels range from 20–40 feet in length and are capable of operating in shallow water close to shore. The fishery is generally short-range, and operators deliver live fish to market or to dockside holding bins daily when weather allows. California scorpionfish is also taken live using hook-and-line gears and as bycatch in the trawl fishery.

Nearshore Landings Information. Landing receipts are the primary source of information for quantifying commercial catch and landings in the nearshore fishery. By law, commercial fish buyers must complete a landing receipt at the time fish are received, purchased, or transferred. Information such as aggregate species weight, price paid, gear used, and condition (e.g., live) must be provided. Considerable effort is spent reviewing and editing landing receipts to ensure information such as species, species' weights, and condition code, is accurately reported. When condition information is missing, it can often be determined by examining the ex-vessel price: a substantially higher price usually indicates a live landing.

Landings information, especially in the 1980s and 1990s was sometimes reported by market category rather than by species. This provided limited information on the species composition of the catch. In recent years, regulations mandating that dealers record landing weights by species for some of the 19 nearshore finfishes has reduced the widespread use of group market categories. Nevertheless, market categories on which this review is based likely contain several different species similar in appearance or market value. For example, the "group gopher" market category often includes gopher, brown, black-and-yellow, grass, kelp, copper, China, and quillback rockfishes. For consistency with previous reports, landings information for market categories is provided in this report.

Data used for this report are preliminary, and live-fish landing weights provided in this review should be interpreted as conservative estimates of the actual live-fish landings in 2004. It should also be noted that condition (live or dead) of fish landed was not required to be reported on landing receipts until 1993; therefore, prior years were not considered in this review. Statewide for 2004, 81% of nearshore fish were reported to be landed live (fig.13); this is down slightly from the 87% reported in 2003.

Regional Landings. Prices and dominant landings varied by management region, ports within a region, and season. Below is a regional summary for 2004.

North Coast Region (Oregon border to Cape Mendocino; Port Complexes of Crescent City and Eureka): Landings in the North Coast Region totaled 73 t, or 30% of nearshore fish landings statewide, with a preliminary ex-vessel value of $0.30 million. Of the total, 73% were landed live. Approximately 27% of the state's live fish were landed in the North Coast Region for a value of $0.24 million. In this region, live landings were dominated by the black rockfish market category (46 t), followed by the cabezon (2 t), and quillback rockfish (1 t) categories. The black rockfish category accounted for 64% of the North Coast Region's landings of live fish and 23% of statewide live landings, as well as 10% of the value of all statewide live landings. Almost 100% of the live fish landings in this region were taken by hook-and-line gear.

North-Central Coast Region (Cape Mendocino to Point Año Nuevo; Port Complexes of Fort Bragg, Bodega Bay, and San Francisco): North-Central Coast Region landings totaled 35 t or 14% of nearshore fish landings statewide with an ex-vessel value of $0.36 million. Sixty-six percent of the total was landed live. The North-Central Region landed approximately 12% of the state's live fish with a value of $0.25 million. The top three market categories landed live were cabezon (10 t), gopher rockfish (4 t), and black-and-yellow rockfish (3 t). These three market categories accounted for 44%, 19%, and 11% of the North-Central Coast Region's landings of live fish, respectively. Hook-and-line gear was used to take 86% of live cabezon landings. Finfish traps are allowed only in certain parts of the North-Central Coast Region. This region had the lowest proportion of live landings.

South-Central Coast Region (Point Año Nuevo to Point Conception; Port Complexes of Monterey and Morro Bay): South-Central Coast Region landings totaled 87.5 t or 32% of nearshore fish landings statewide with an ex-vessel value of $1.06 million. Of these 87.5 tons, 79 t (90%) were landed live—the highest proportion of any region. Approximately 40% of the state's live fish were landed in this region for a value of $1.02 million. Live landings were dominated by cabezon (29 t) and brown rockfish (22 t), accounting for 65% of the South-Central Coast Region's landings of live fish, followed by grass (10 t), gopher (9 t), and black-and-yellow (6 t) rockfish market categories.

South Coast Region (Point Conception to México border; Port Complexes of Santa Barbara, Los Angeles, and San Diego): South Coast Region landings totaled 52 t or 21% of nearshore fish landings statewide with an ex-vessel value of $0.48 million. Forty-four tons were landed live, representing 84% of the regional total. About 22% of the state's live fish were landed in the South Coast Region for a value of $0.43 million. In 2004, live landings of California sheephead dominated the landings (32 t), followed by cabezon (5 t), grass rockfish (2 t), and California scorpionfish (2 t). All together, these categories accounted for 94% of the South Coast Region's landings of live fish. Eighty-six percent of the sheephead landings were taken using trap gear.

Recent Trends in the Fishery. Preliminary data for 2004 indicate that landings of live fish leveled off following a decline from a peak in 1998 (453 t landed). Beginning in 1999 and 2000, changes in federal and state regulations, which limited landings, accounted for much of the observed decline. In addition, the 2004 total value of the fishery also leveled off (fig. 12) compared to the previous year.

Total nearshore landings increased slightly from 2003 to 2004, although there was a small decrease in the number of nearshore permittees. An increase in the 2004 black rockfish optimal yield (OYs) was accompanied by increases in trip limits for certain species. Increased trip limits may have provided an economic incentive for certain permittees who would otherwise not have fished. Conversely, the California sheephead TAC decreased in 2004, providing less opportunity for that species in the southern region. Nearshore effort and landings continued to be tied to low federal trip limits and depth restrictions designed to protect overfished species such as bocaccio, canary and yelloweye rockfishes, and lingcod.

Nearshore Fishery Management Plan Implementation. The Nearshore Fishery Management Plan (NFMP), adopted in 2002, is a framework plan that identifies a management strategy for many of the nearshore species targeted by the nearshore live-fish fishery. Five management approaches (Fishery Control Rule, Regional Management, Allocation, Marine Protected Areas, and Restricted Access) form the basis for integrated management strategies that, over time, will meet the goals and objectives of the Marine Life Management Act (MLMA) and provide for sustainable nearshore stocks and fisheries. Since the NFMP was adopted, management has improved and will continue to do so as we implement these approaches and our knowledge base increases.

- *Use of the NFMP Fishery Control Rule:* The NFMP relies on an information-based harvest strategy that uses an increasing level of knowledge to establish harvest limits; it is more conservative than the current control rule for federal groundfish utilized by the PFMC. As more information becomes available, for example through formal stock assessments and improved essential fishery information, harvest limits can be modified. For example, catch limits may be adjusted based on estimates of existing stock relative to unfished levels rather than based on a portion of recent landings. Assessment scientists used this fishery control rule formula in 2003 to calculate harvest limits for cabezon and black rockfish, which were adopted by state and federal regulatory agencies in 2004.
- *The Restricted Access Program:* A full restricted access program was implemented for the shallow nearshore species (cabezon, California sheephead, greenlings, California scorpionfish, and black-and-yellow, China, gopher, grass, and kelp rockfishes) in 2003. Nearshore Fishery Permit (NFP) holders now have regional permits that only allow them to use hook-and-line gears. A regional gear endorsement also allows the use of trap gear. A total of 216 NFPs were issued in 2003, and a total of 202 permits were issued in 2004, resulting in an annual attrition rate of about seven percent.

  A nontransferable Deeper Nearshore Species Fishery Permit (DNSFP) was first required in 2003 to take black, blue, brown, calico, copper, olive, quillback, and treefish rockfishes. There were 286 permittees in 2003 and 246 permittees in 2004, resulting in an attrition rate of nine percent.
- *Regional Management:* Regional management of the nearshore fishery depends on the ability to monitor both recreational and commercial landings by geographic area. Previously, only the commercial sector of the fishery could be monitored on a regional basis. The new California Recreational Fishery Sampling program was implemented in 2004, making regional recreational estimates possible. This new level of precision is expected to further efforts to develop region-based management for the nearshore fishery.
- *Marine Protected Areas:* Implementation efforts have been directed toward evaluating the available information on appropriate habitat for the NFMP species in and around Marine Protected Areas (MPAs), with an emphasis on southern California species. This effort will help determine the adequacy of utilizing existing MPAs as reference reserves for NFMP species. It may eventually provide time series data on nearshore fish abundance resulting from monitoring both inside and outside reserves.

Pacific Herring

California's Pacific herring (*Clupea pallasi*) fisheries had mixed success in 2004. Statewide landings for the 2003–04 sac roe season (December 2003–March 2004) totaled 1,651 t, a decrease of 16% from the 2002–03 landings of 1,975 t, with permittees in all fishing areas not reaching their quotas. The San Francisco gill net fleet, composed of three platoons (418 active permits), landed 1,397 t, 23.7% under the 1,833 t quota. The Tomales Bay fishery (36 permits) landed a total of 253.7 t of the 453.6 t quota. No fishing effort took place in Crescent City (three permits) with a 27.2 ton quota, and Humboldt Bay landings (four permits) totaled only 0.53 tons, far below the 54.4 ton quota for that fishery. Annual sac roe landings January to December 2004 decreased from 1,780 t to 1,596 t, down 10.3% from the previous year (tab. 1).

Catch value in the herring sac roe fishery is based on roe recovery rates. Ex-vessel prices for herring with 10% roe recovery averaged an estimated $500 per short ton for gill-net landings, with an additional $50 paid for each percentage point above 10%. This is the third consecutive season that the ex-vessel price per ton has been well below the 10-year average of $873, reflecting the continuing volatility of the Japanese economy. The statewide ex-vessel value of the sac roe fishery fell to $879,500 in 2004, the lowest value for this fishery in 10 years at only 15.7% of the average value per year for the previous nine seasons ($5.6 million). Since the 1997–98 season, the San Francisco Bay herring eggs-on-kelp fishery landings have been below average. Landings totaled 5.7 t, which was only 16.1% of the 35.3 t quota and an 88.7% decrease from last season's landings of 53.3 t. The total estimated value of the 2003–04 eggs-on-kelp harvest was approximately $43,712 based on an average ex-vessel price of $3.50/lb. Under favorable market conditions, the price paid for herring eggs-on-kelp may vary with the product's grade, with grade 1 receiving approximately $10/lb, and grade 5 bringing $3–4/lb.

CDFG conducted research surveys in three bays to estimate the spawning biomass of each herring stock. Spawn deposition survey estimates were used to assess San Francisco, Tomales Bay, and Humboldt Bay populations.

The 2003–04 herring spawning biomass estimate for the San Francisco Bay population was 31,207 t, which is 25.4% below the 30-year average (41,845 t). There was no herring spawning biomass estimate for the 2002–03 season. The age composition of the 2003–04 San Francisco Bay population, based on current otolith readings, reflects a continued depressed age structure that has been observed since the 1997–98 El Niño season. The 2003–04 spawning biomass estimate for Tomales Bay was 10,999 t, which represents an increase of 176.6% over the 2002–03 biomass estimate (3,975 t). This estimate is the largest since the re-opening of the Tomales Bay herring sac roe fishery in the 1992–93 season and the second largest recorded since the CDFG first initiated annual population assessments in Tomales Bay during the 1972–73 season. In Humboldt Bay, CDFG conducted spawning ground surveys and monitoring of the herring gill net fishery for the fourth consecutive season. The 2003–04 spawning biomass estimate for Humboldt Bay was 459 t, an increase of 199.4% over the 2002–03 biomass estimate (153 t). No surveys were conducted in Crescent City Harbor.

The herring roe product, "kazunoko," remains an integral part of traditional Japanese New Year's festivities. However, changes in the Japanese culture and economy have also resulted in changes to the sac roe market. Industry observers expect demand for kazunoko to wane as younger Japanese become more westernized. Ex-vessel prices are expected to remain low with concern for the Japanese economy, and herring buyers will proceed cautiously by offering similarly low prices in the 2003-04 season.

Recreational Fishery

Recreational ocean fishing in California takes place from piers, shorelines, private vessels, and CPFVs across more than 1,100 miles of coastline. To more efficiently monitor the catch of over 1 million saltwater sport anglers and divers, the CDFG implemented the CRFS program in January 2004.

The CRFS is a new method for estimating total marine recreational finfish catch and effort in California. The program is a coordinated sampling survey designed to gather catch and effort data from anglers in all modes of marine recreational finfish fishing. This survey incorporates and updates the sampling methodologies of the National Marine Fisheries Services' Marine Recreational Fisheries Statistics Survey (MRFSS) and the CDFG's Ocean Salmon Project. The CRFS program includes many changes and improvements over previous surveys, such as high-frequency, on-site sampling, on-site estimates of private boat effort, emphasis on species of concern, and use of an angler license database to estimate effort when it cannot be estimated directly from field sampling.

The CRFS was created in response to the concerns of fishery managers and constituents over using MRFSS to make in-season management decisions. The primary goal of CRFS is to provide fishery managers with more accurate and timely marine recreational fishery-based data in order to make necessary adjustments and avoid in-season closures. In 2004, there were several in-season adjustments made to recreational groundfish regulations. On 1 March, recreational groundfish was closed on the Cordell Bank (off Marin county) to reduce incidental take of canary rockfish. On 1 April, the daily bag limit on lingcod went from two fish to one fish per day, and the size limit increased from 24 to 30 inches. On 16 May, fishing for black rockfish was closed in state waters north of 40°10'N latitude.

The CRFS sampling effort in 2004 increased substantially from MRFFS sampling effort in 2003. The number of recorded fish lengths went up 109% (88,665) from 2003 (42,462), while the total number of fish counted went up 250% (220,567) from 2003 (63,019). The number of anglers interviewed increased by 276% (126,814) from 2003 (33,748), and the number of assignments completed rose by 117% (4,097) from 2003 (1,888). Additionally, the number of CRFS samplers working in the field doubled from 26 in 2003, to 52 in 2004.

The CRFS tabulates catch and effort estimates by year, month, coastal district, trip target type, marine area, and fishing mode. The four types of fishing modes are man-made (piers and jetties), beaches and banks, party and charter boats, and private or rental boats. All recreational finfish catch and effort in California can be categorized into one of these modes. In 2004, the CRFS estimated over 4.4 million individual recreational fishing trips occurred in California waters (tab. 7). The large majority of sportfishing trips (2.7 million) were in man-made mode and most of those trips were on public piers. Public piers serve as the most affordable and convenient sportfishing platform for anglers in California. Traditionally popular target species on public piers include Pacific bonito, Pacific mackerel, Pacific sardine, California halibut, rockfish, California corbina (*Menticirrhus undulatus*), and embiotocids (perches). During warm water events, jumbo squid (*Dosidicus gigas*) can be caught in large numbers off piers, as well as by boat anglers, but in 2004 they weren't a significant part of the recreational catch in either mode. The CRFS does not produce estimates of jumbo squid, but samplers do observe catch and dorsal mantle length data.

The top-ten species landed in 2004 (CRFS estimates in metric tons) by recreational anglers and divers from

TABLE 7
Estimate of Individual Fishing Trips Made by Fishing Mode in 2004

Mode	Number of fishing trips
Man-made	2,742,000
Beach bank	302,000
Party/Charter vessels	711,000
Private vessels	659,000
Total	4,414,000

TABLE 8
Estimated Recreational Landings (metric tons) by Fishing Mode in 2004*

Common Name	Total	Man Made	Beach/ Bank	Party/ Charter Boat	Private/ Rental Boat
Barred sandbass	791	4	3	417	368
Pacific barracuda	502	17	—	423	62
Yellowtail	380	—	—	176	204
Pacific bonito	359	201	12	100	47
Pacific mackerel	329	243	1	20	64
Kelp bass	328	2	6	216	104
Vermilion rockfish	212	0	3	140	69
California halibut	185	16	—	36	134
Albacore	181	—	—	27	154
Blue rockfish	160	0	8	110	42
Lingcod	122	2	12	43	66
Black rockfish	106	1	4	28	74
Barred surfperch	86	13	73	0	0
Jacksmelt	69	64	5	0	1
Pacific sardine	67	66	—	0	0
Bocaccio	61	—	—	54	7
Olive rockfish	55	0	2	44	9
Striped bass	52	6	1	9	35
Bat ray	49	40	6	0	3
Pacific sanddabs	43	1	0	26	16
Totals	4,137	676	136	1,868	1,458

*CRFS does not include estimates of chinook salmon.

all modes combined were barred sandbass, California barracuda, yellowtail, Pacific bonito, Pacific mackerel, kelp bass, vermilion rockfish (*Sebastes miniatus*), California halibut, albacore, and blue rockfish (tab. 8). With the exception of Pacific mackerel and Pacific bonito, the majority of the top-ten species landed were taken by party/charter or private/rental boats.

Barred sandbass, California barracuda, and yellowtail were staples of the fleet south of Point Conception. These species are a common part of the catch in southern California throughout the year, but effort and catch greatly increases in the summer months. 2004 saw the return of Pacific bonito as a significant part of the sport catch in southern California. Pacific bonito were a substantial part of the catch in all fishing modes from spring through the remainder of the year. Catch peaked in the summer when Pacific bonito were the most abundant species landed on public piers. While albacore made the top-ten species landed in California waters in 2004, California anglers landed the majority of albacore in Mexican waters.

Southern California vessels frequently target species in waters south of the border. Fish caught in Mexican waters and landed in California ports do not count toward state or federal quotas (if a quota exists for a species). While the CRFS technicians do sample these trips, the CRFS estimates don't include catch that is harvested outside of state waters and then landed in California ports.

The number of trips by private vessels and CPFVs into Mexican waters has been increasing in recent years due to both excellent albacore fishing and restrictions on groundfish species. The size of the long-range CPFV fleet in San Diego has also been increasing. The long-range fleet specializes in five to 21 day trips south of the border to target species such as wahoo (*Acanthocybium solanderi*), dolphinfish, yellowfin tuna, yellowtail, and albacore.

In addition to the CRFS, the CDFG collects and maintains a database derived from mandatory logbook information supplied by CPFVs. Much of our historical and current knowledge of CPFV recreational fishing in California is based on the logbook data. The CPFV logbook data are also used to validate CRFS party/charter boat estimates.

The estimates from the MRFSS program are not directly comparable to the CRFS program. Most of the survey methodologies from the CRFS program are significantly different from those of the MRFSS program. Two programs must be calibrated so that the long time series of recreational data can be used with these new data. The CDFG, along with the Pacific States Marine Fisheries Commission Recreational Fisheries Information Network statistical committee, will undertake the task during the coming months.

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THE STATE OF THE CALIFORNIA CURRENT, 2004–2005: STILL COOL?

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ABSTRACT

This report summarizes the recent state of the California Current System (CCS), primarily during the period of April 2004 to January 2005. The report is based on observations made between Oregon and Baja California by various ocean observing programs. The CCS was not forced by any coherent basin-wide processes during the observation period. The weak tropical El Niño of 2004 did not appear to have had a noticeable effect on the CCS. However, the CCS remains in a cold phase, a state it has had since the 1999 La Niña phase. Some biological parameters show a distinct response to this state, i.e. zooplankton biomass and its species richness, others display a mixed response such as the CCS avifauna and its productivity, and some do not show any response, such as phytoplankton biomass and Pacific sardine (*Sardinops sagax*) productivity. Over all, the state of the system remains "normal" with respect to its climatology. The unusual intrusion of cold and fresh subarctic water into the CCS is waning off Oregon but still noticeable off southern California and off Baja California. Because the CCS does not appear subject to coherent basin-wide forcing, the outlook for the CCS over the next years is uncertain

INTRODUCTION

This is the 12th in a series of annual reports since 1993 summarizing the climatology, oceanography, and biology of the California Current System (CCS). This report is based on observations taken between Oregon and Baja California between the spring of 2004 and 2005. The programs or institutions contributing to this report are the U.S. Global Ocean Ecosystem Dynamics Long-Term Observation Program (GLOBEC LTOP) working off Oregon, the Pacific Fisheries Environmental Laboratory (PFEL) providing basin- and coast-wide climatologies, the Point Reyes Bird Observatory (PRBO) working off Central and Southern California using seabirds as ecosystem indicators in the CCS, the Monterey Bay Aquarium Research Institute (MBARI) Monterey Ocean Time series and Observatory (MOTO), the NOAA Pacific Coastal Ocean Observing System (PaCOOS) program off Central California, the CalCOFI program working off Southern California, and the Investigaciones Mexicanas de la Corriente de California program (IMECOCAL) working off Baja California.

The most significant event affecting the CCS over the last decade was the switch of the sign of the Pacific Decadal Oscillation index (PDO; Mantua et al. 1997), which had been positive from the mid-1970s until 1998, the most recent warm period. The switch of the PDO coincided with an extremely strong ENSO event, 1997/98. Initially, dramatic changes in zooplankton community structure were observed in the CCS during the cold period that began in 1999 (Brinton and Townsend 2003; Lavaniegos and Ohman 2003; Peterson and Schwing 2003) and were consistent with our expectations for such a cold period. Subsequently, however, climatic indices have gone bland. Sea surface temperature patterns in the North Pacific no longer resemble the canonical PDO warm or cold patterns; a newly "minted" ocean climate mode (Bond et al. 2003), called the Victoria mode, is no longer noticeable, and anomaly fields for most properties suggested that the North Pacific and the CCS had entered an unusual period of "normality" (Goericke et al. 2004). A tropical El Niño during this time period, observed in 2002/03, also failed to have a significant effect on the CCS (Venrick et al. 2003).

Nonetheless, the CCS did not cease to surprise us over the last five years. Most interesting was the intrusion of cold and fresh subarctic water masses into the CCS, which was first noticed off British Columbia and Oregon (Freeland et al. 2003) but quickly spread further south (Venrick et al. 2003; Goericke et al. 2004; Durazo et al. 2005). This intrusion was likely due to the weakening of the Davidson Current flowing into the Gulf of Alaska and the intensification of the California Current (Freeland et al. 2003; Wheeler et al. 2003). Last year, we speculated that this may have been driven by a spin-up of the central North Pacific gyre (Chavez et al. 2003; Goericke et al. 2004), either due to ephemeral changes in atmospheric forcing or due to changes in forcing associated with the recent shifts in climate indicators. Effects of this increased flow of subarctic water masses into the CCS region on the ecosystem were dramatic off Oregon (Wheeler et al. 2003), but likely obscured off California by the co-occurring 2002/03 El Niño (Bograd and Lynn 2003).

This report will focus on a description of the state of the CCS between the springs of 2004 and 2005, using simple descriptors such as hydrographic properties, flow-, temperature-, and salinity-fields, biological indicators such as biomass found at different trophic levels, and the distribution and abundance of indicator species. The relationships we hope to understand are the physical and chemical responses of the CCS to changes in the major indices of ocean climate and the consequent effects on the biomass and species composition of the ecosystem. Unlike recent years, there was no single climatological or environmental factor that clearly influenced a large portion of the CCS during 2004. Regional changes appeared to result from the waning of the subarctic intrusion (Venrick et al. 2003), which was confounded by anomalous warming in the north and superimposed on local influences.

DATA SETS AND METHODS

Basin- and Coast-Wide Analyses

Large-scale patterns are summarized from the National Center for Environmental Prediction Reanalysis fields (Kistler et al. 2001) and from the NOAA-CIRES Climate Diagnostics Center (http://www.cdc.noaa.gov/). The reanalysis fields are monthly gridded (approximately 2° × 2°) anomalies of sea surface temperature (SST) and surface winds. The base period is 1968–96. Monthly upwelling indices and their anomalies for the North American west coast (21°–52°N) are calculated relative to 1948–67. The daily alongshore wind component and SST are from the NOAA National Data Buoy Center (NDBC). Values from six representative buoys from the CCS are plotted against the harmonic mean of each buoy.

Regional Analyses–Oregon

Regular sampling of the Newport Hydrographic (NH) line along 44.65°N by the GLOBEC Northeast Pacific Long-Term Observation Program (LTOP) ended in September 2003. Nevertheless, several sections were made along this line in 2004: in late summer (30 August–1 September) by GLOBEC LTOP and in spring (9–10 May), early summer (26–27 June), and fall (7–8 November) by the NOAA PaCOOS program. As in previous years, conductivity-temperature-depth (CTD) casts were made at 12 standard stations at locations between 3 and 157 km from shore. CTD casts sampled at least 90% of the water column over the continental shelf and upper slope and sampled to 500 m or 1000 m in deep water. Zooplankton are sampled with a 0.5 m net (0.2 mm mesh) towed vertically from 100 m to the surface or, in shallower water, from 3 m above the sea floor to the surface. Zooplankton are enumerated by species and developmental stage, and biomass is calculated by multiplying species abundance by individual carbon weight, then summing across stages and species. Total biomass of all copepod species are reported here. Copepod species richness is calculated as the number of taxa present in a given sample. To de-trend seasonal signals of species richness, individual samples were first smoothed by converting to monthly averages and then calculated as monthly anomalies (i.e. climatological monthly mean subtracted from the year-specific monthly average).

Regional Analyses–Monterey Bay

Monterey Bay region time series consist of two moored telemetering buoys located in the Bay, hydrographic surveys of the Bay every three weeks, and quarterly surveys along CalCOFI lines 67 and 60 from the coast to station 90. Stations are sampled to near bottom or 1012 m where water depth permits. Parameters measured are similar to those for the CalCOFI program described below and methods are described in Chavez et al., 2002. Properties are mapped for each section and can be viewed at <www.mbari.org/bog/projects/secret/default.htm>.

Regional Analyses–CalCOFI

The CalCOFI program conducts quarterly surveys off Southern California, covering 66 stations (fig. 1);

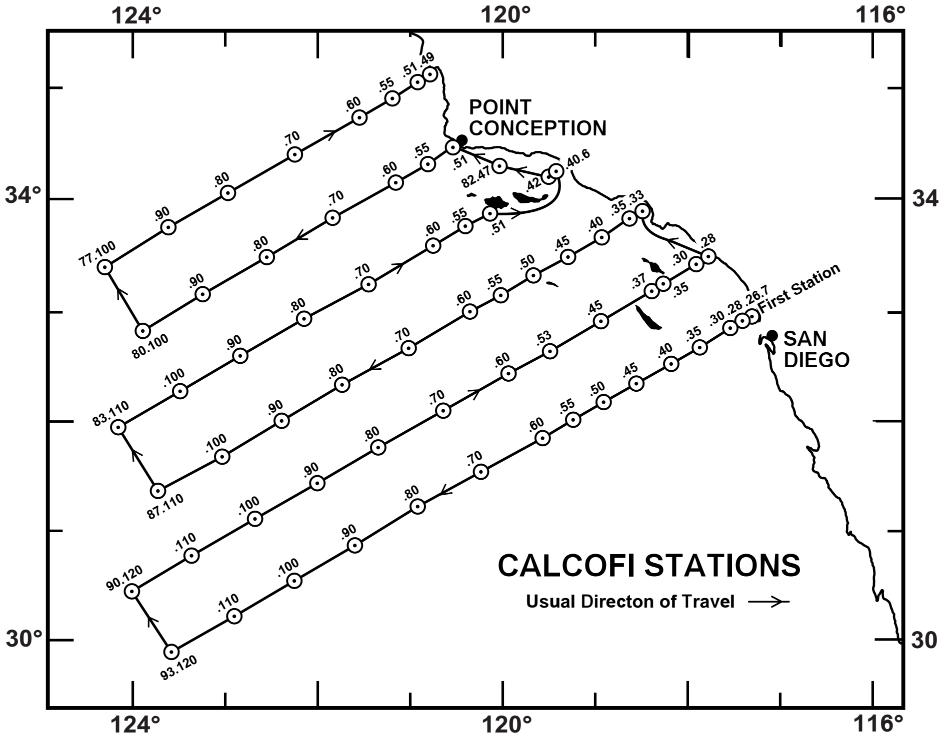

FIGURE 1

Figure 1. The standard CalCOFI station pattern. All 66 stations are occupied on most cruises. During the winter and spring cruises the pattern is extended north for observations of hydrographic properties and distributions of fish eggs.

results from surveys between April of 2004 and January 2005 are discussed here. Water column properties (conductivity, temperature, pressure, oxygen, fluorescence, and light transmission) were measured down to 525 m. Salinity, dissolved oxygen, nutrients, and chlorophyll are determined on 12 to 20 water samples collected throughout the water column. Standard (.505 mm mesh) oblique bongo tows are conducted to 210 m depth at each station, bottom depth permitting. Detailed descriptions of sampling and analytical protocols and data reports from past cruises are archived on the CalCOFI website (http://www.calcofi.org). Climatologies were calculated for various parameters; these are based on the 1984 to 2005 time period. Cruise averages were calculated for these parameters from individual station data. Anomalies were calculated as parameter value minus harmonic mean.

Regional Analyses–IMECOCAL

The IMECOCAL monitoring program began in autumn 1997, consisting of quarterly cruises surveying the area of a reduced CalCOFI grid of about 93 stations off Baja California, México (fig. 2). The core oceanographic data set collected at each station includes a CTD/Rosette cast to 1000 m depth, with sensors for pressure, temperature, salinity, dissolved oxygen, and fluorescence. Water samples from the upper 200 m are collected with 5 liter Niskin bottles at 0, 10, 20, 50, 100, 150, and 200 m depths to determine dissolved oxygen, phytoplankton pigments (chlorophyll *a* and phaeopigments), nutrients (NO3, NO2, PO4, SiO3), and primary production. IMECOCAL cruise schedules, data collection, methods, and analysis are fully described at <imecocal.cicese.mx>.

Avifauna

Systematic surveys of the distribution and abundance of marine birds have been made on CalCOFI cruises since spring of 1987 (Hyrenbach and Veit 2003). Personnel from the Point Reyes Bird Observatory (PRBO) Conservation Science conducted at-sea surveys during 2004. Additionally, PRBO has monitored the reproductive performance and diet of seabird populations breeding at the Farallon Islands (37°N, 123°W) since the early 1970s (Sydeman et al. 2001).

BASINWIDE PATTERNS

The SST anomaly patterns during the first three months of 2005 did not resemble any of the characteristic spatial patterns defined in previous analyses (i.e., the PDO, Mantua and Hare 2002; and the Victoria mode, Bond et al. 2003). A weak El Niño evolved in the tropical Pacific in 2004 (NOAA CPC Climate Diagnostics Bulletin, http://www.cpc.ncep.noaa.gov). The MEI (Multivariate ENSO Index, Wolter and Timlin 1998), which indicates El Niño conditions, has maintained pos-

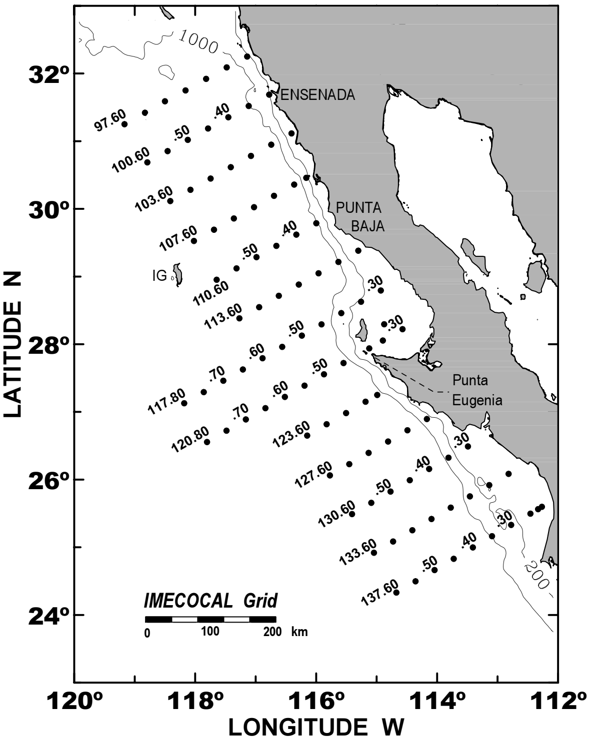

Figure 2. The standard IMECOCAL sampling grid. Solid dots represent the 93-station pattern (CalCOFI lines 100 to 137) occupied by the IMECOCAL program since 1997 (including line 97 for April surveys since 2003). Depth contours are in meters.

itive values since early 2002, although their magnitude has remained in the weak to moderate range. Associated with the 2004 event were warm upper ocean anomalies that developed in the central tropical Pacific (fig. 3). However, this warm anomaly did not propagate east to the South American coast, an evolution characteristic of El Niño, and, instead, cooler than normal SSTs prevailed along the South American coast throughout this event.

Despite the continuing signature of a weak El Niño, the atmospheric variability over the past two years has been dominated by the 60–90 day signal of the Madden-Julian Oscillation (MJO). The effect of the MJO is reflected in the extra-tropical North Pacific atmosphere and upper ocean anomalies as well, making it difficult to characterize any persistent long-term anomaly pattern. The predominant MJO forcing has also excited atmospheric variability at relatively short wavelengths (subocean basin), which may have contributed to the recent spatially complex and heterogeneous SST anomaly patterns. Patterns like the PDO are typically associated with much longer atmospheric wave patterns.

In the CCS, SST anomalies have been generally positive since early 2004. Although due to the strong MJO activity, a specific pattern did not persist for more than a few months. The anomaly maps in Figure 3 represent the predominant seasonal variability during the past year,

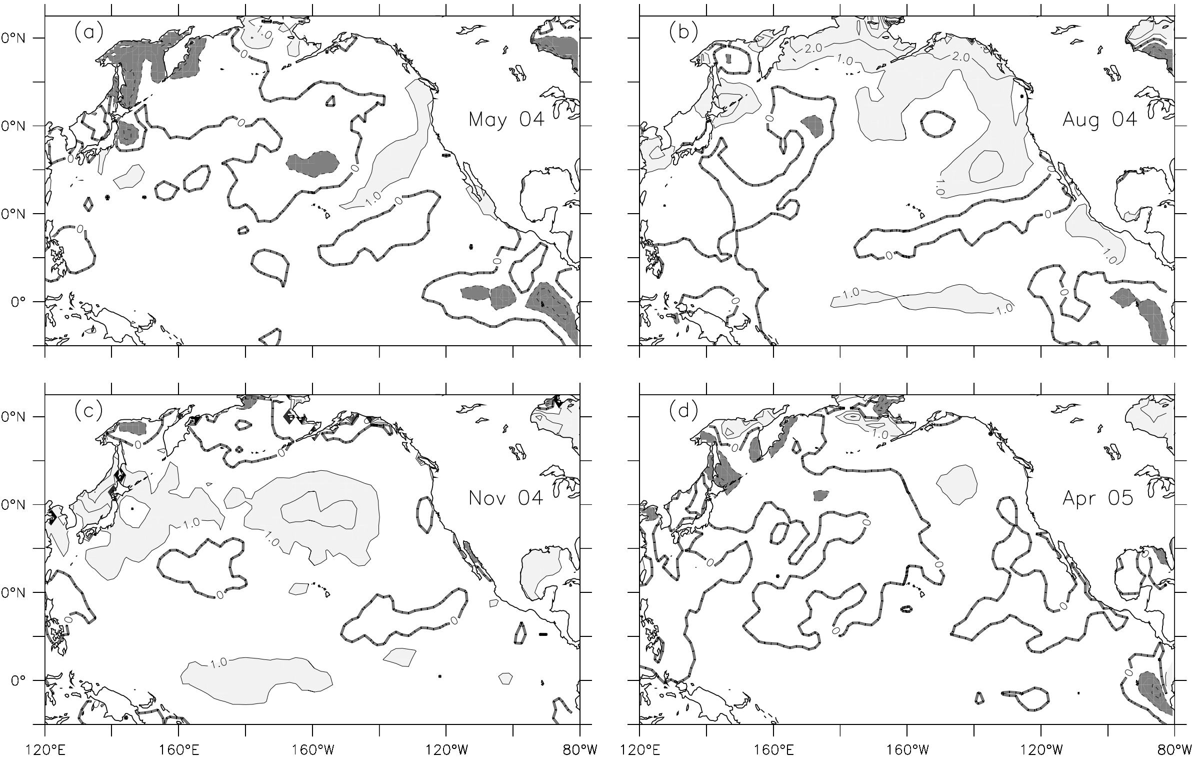

Figure 3. SST anomalies in the North Pacific Ocean for (a) May 2004, (b) August 2004, (c) November 2004, and (d) April 2005. Contour interval is 1.0°C. Positive (warm) anomalies are shaded light grey, and negative (cool) anomalies are shaded dark grey. SST climatology is 1968–96. Monthly data obtained from the NOAA-CIRES Climate Diagnostics Center.

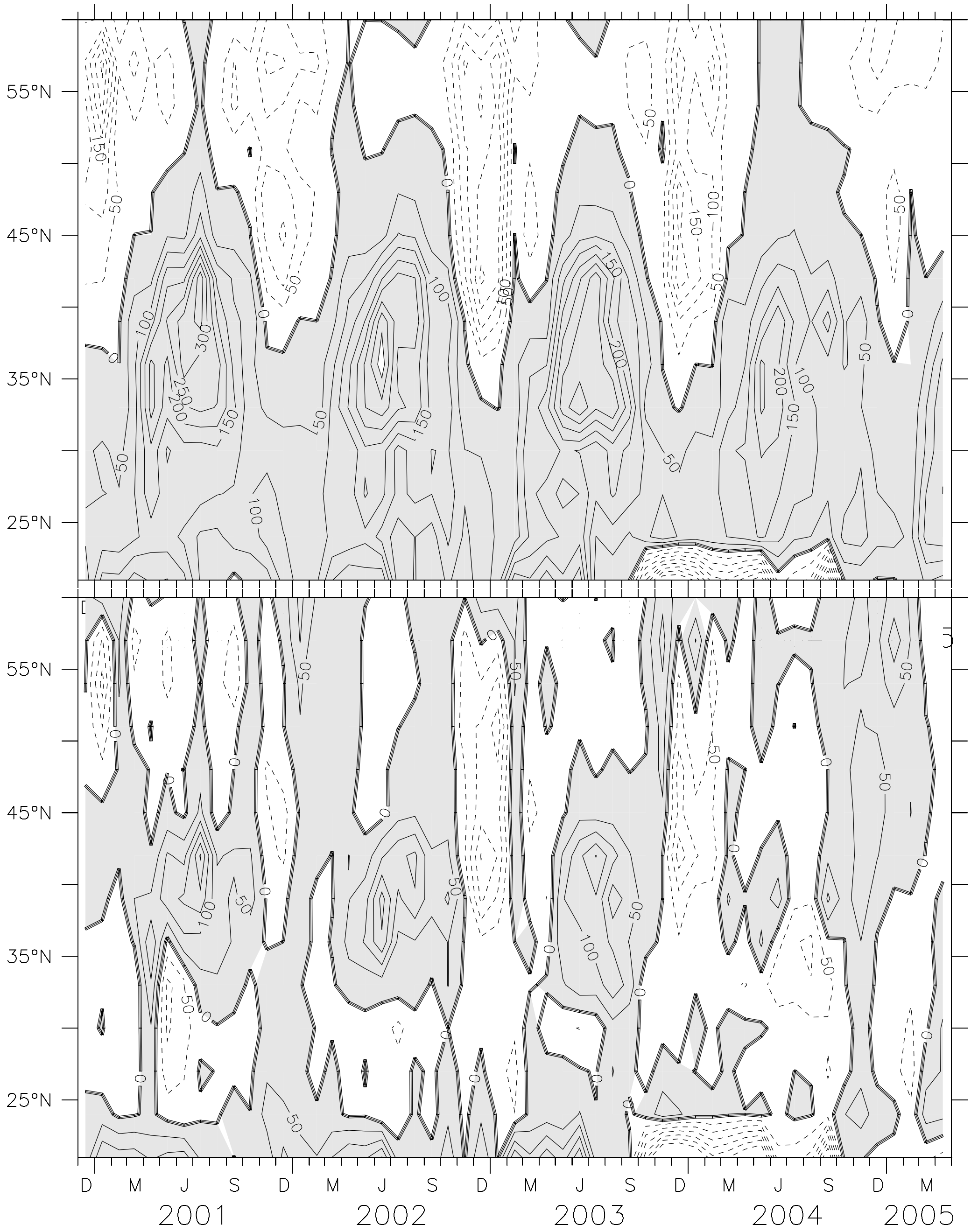

Figure 4. Monthly upwelling index (upper panel) and upwelling index anomaly (lower panel) for Jan. 2001–Apr. 2005. Shaded areas denote positive (upwelling-favorable) values in upper panel, and positive anomalies (generally greater than normal upwelling) in lower panel. Anomalies are relative to 1948–67 monthly means. Units are in m³/s per 100 km of coastline.

but the abrupt intra-seasonal shifts are unusual. SSTs were unusually warm in spring 2004, especially in the northern CCS. These anomalies peaked in summer, particularly in the northern Gulf of Alaska and Bering Sea, before declining in fall 2004. Most recently (spring 2005), surface waters of the CCS have remained anomalously warm. We believe this is due to anomalous regional winds, which are responsible for less upwelling at the coast and in the open ocean, and reduced mixing. However, the lack of temperature measurements at depth make it difficult to determine the cause of this long-term warm state or how likely it is to remain.

COASTWIDE CONDITIONS

Monthly coastal upwelling indices (Bakun 1973; Schwing et al. 1996) support the contention that upwelling winds in the CCS have been unusually weak in the past year (fig. 4). The evolution of upwelling index

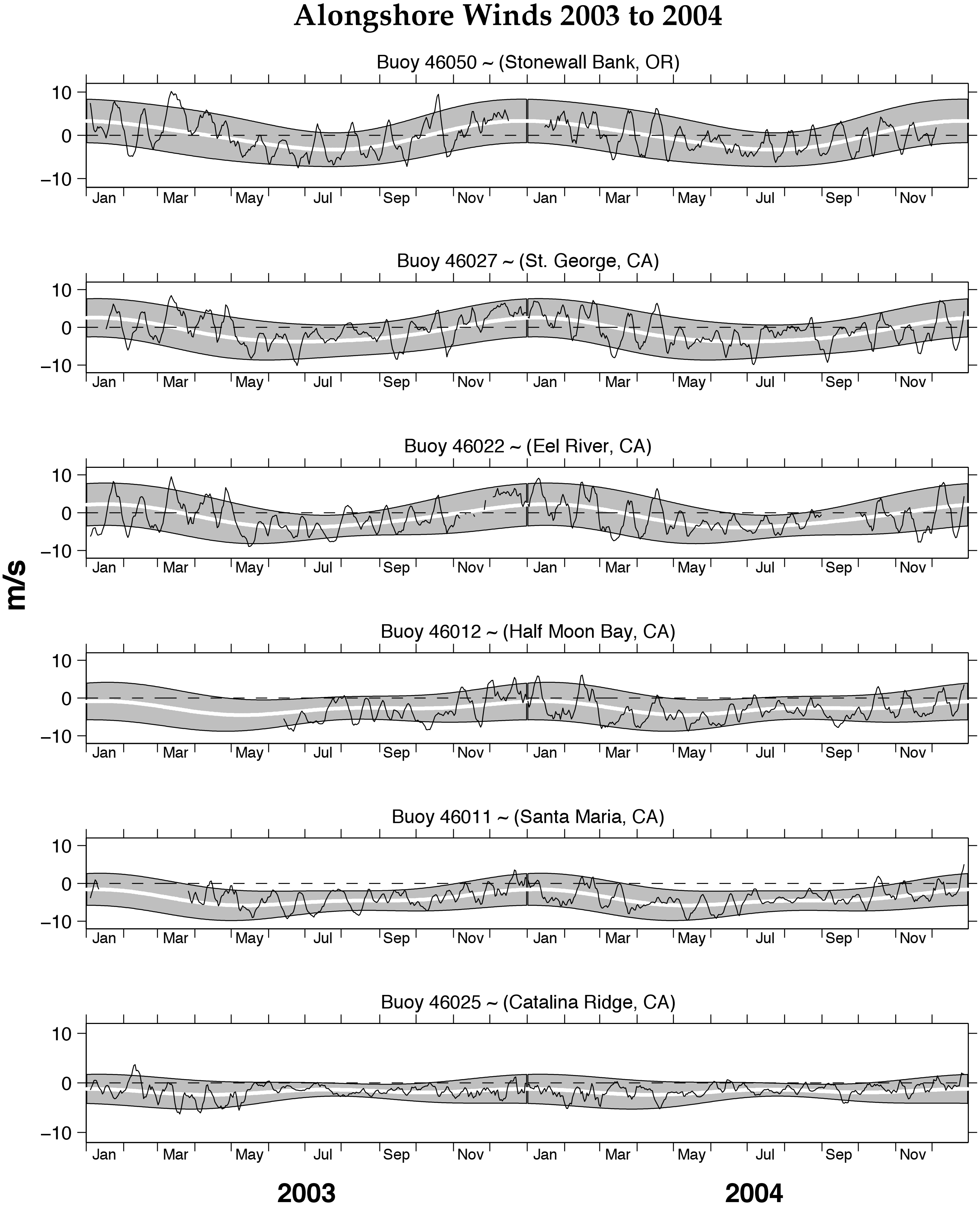

Figure 5. Time series of daily-averaged alongshore winds for Jan. 2003–Dec. 2004 at selected NOAA National Data Buoy Center (NDBC) coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Series have been smoothed with a 7-day running mean. Data provided by NOAA NDBC.

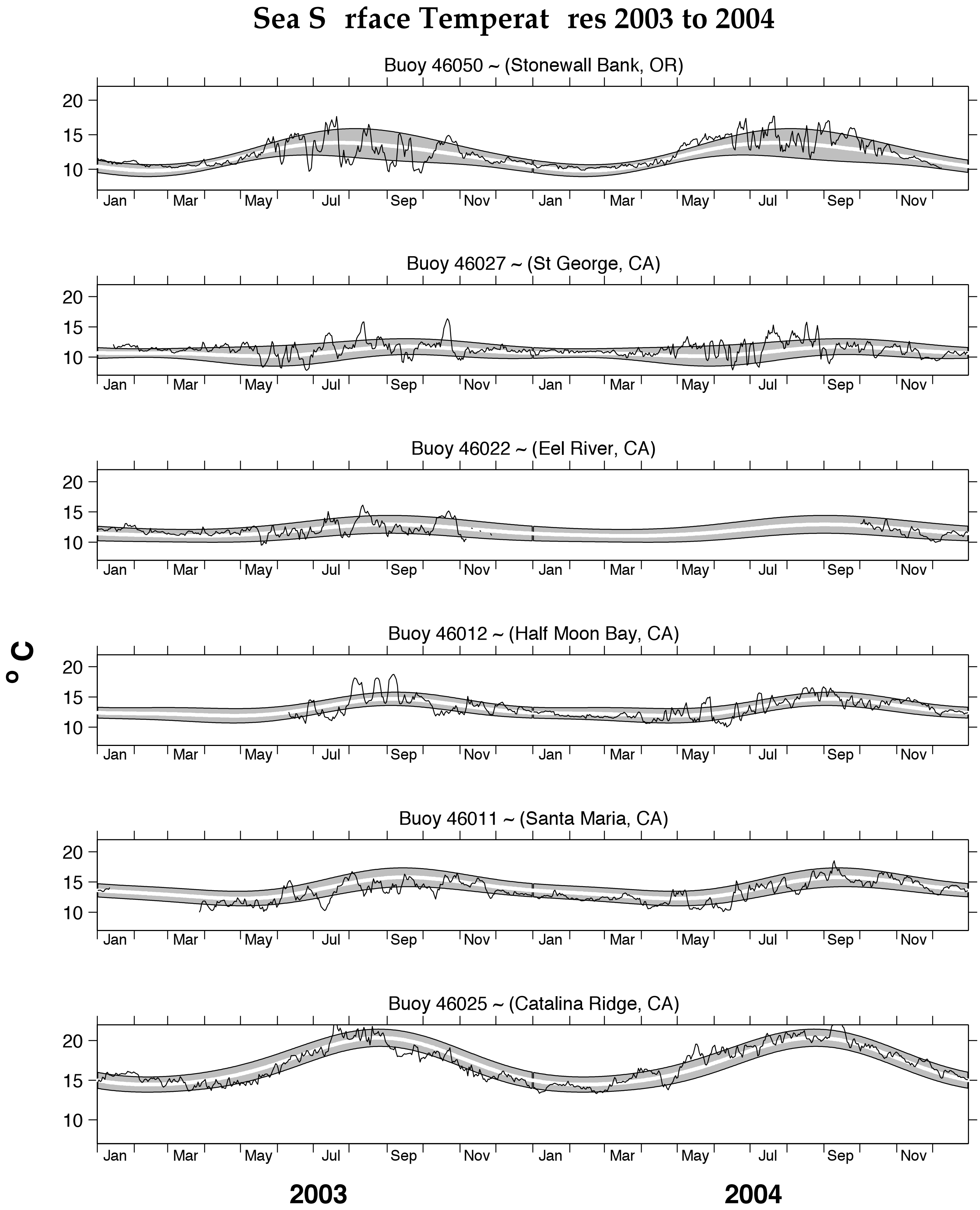

Figure 6. Time series of daily-averaged SST for Jan. 2003–Dec. 2004 at selected NDBC coastal buoys. Bold lines are the biharmonic annual climatological cycle at each buoy. Shaded areas are the standard errors for each Julian day. Data provided by NOAA NDBC.

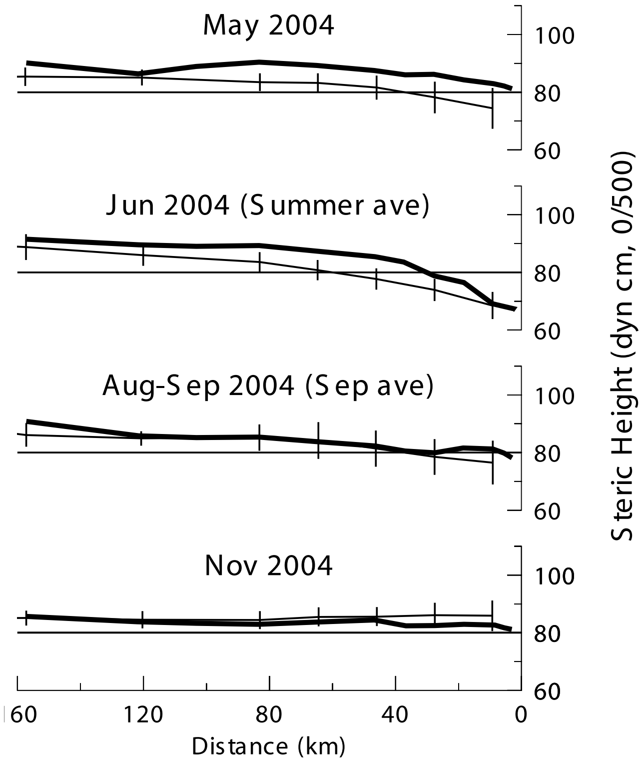

Figure 7. Offshore profiles of steric height (geopotential anomaly, surface relative to 500 dbar, J/kg) along the NH-line. Each panel shows the 2004 values and the corresponding historical (1961–71) average with plus/minus one standard deviation (Smith et al. 2001). Values over the shelf and upper slope were calculated by the method of Reid and Mantyla (1976).

anomalies (weakly negative in summer 2004 to weakly positive in fall) matches the large-scale SST anomalies (fig. 3). The period 2004–05 differs from recent years. Since 1999, the CCS has featured winters with weak upwelling, followed by anomalously strong summer upwelling (Hayward et al. 1999; Bograd et al. 2000; Durazo et al. 2001; Schwing et al. 2002; Venrick et al. 2003; Goericke et al. 2004). In the past year, the summer of 2004 featured negative upwelling index values (weak upwelling) and positive anomalies in late fall and winter. Negative anomalies continued through spring 2005 over much of the West Coast. Not until July 2005 (not shown) did strong upwelling return to the northern CCS, while weaker than normal upwelling continued farther south. Significant biological effects, including increased seabird mortality throughout the region[1], appeared to be associated with this unusually late transition to upwelling.

The predominance of strong intraseasonal variability in the CCS is illustrated by a series of ca. 30-day, alongshore fluctuations in the National Data Buoy Center (NDBC) coastal buoy winds (fig. 5). These strong fluctuations or reversals in the alongshore winds were observed throughout the 2003–04 period, particularly in the northern CCS. The contrast between the 2003 and 2004 upwelling seasons is also clear. Summer 2003 winds were persistently to the south, indicating normal upwelling-favorable conditions in the northern CCS. In summer 2004, however, weaker equatorward winds prevailed. Stronger upwelling-favorable winds did not return until unusually late in the year, around October-November. A similar late transition to upwelling-favorable conditions occurred in 2005.

This anomalous wind forcing is reflected in the SST time series from the NDBC buoys (fig. 6). The intraseasonal oscillations in alongshore winds in summer and fall 2003 resulted in strong fluctuations in SST, with changes sometimes exceeding 5°C over the course of a few days. Winter temperatures showed much smaller fluctuations and were near climatological values throughout the CCS. Unseasonably warm SSTs prevailed in summer 2004, especially in the northern CCS. But the anomalously strong southward winds in late fall led to a rapid cooling of SST to near climatological levels. Upper ocean temperatures appeared to be very warm in early spring 2005 (not shown), but there has been no apparent surface ocean teleconnection with the tropical Pacific.

REGIONAL STUDIES

Oregon Coast: GLOBEC LTOP and NOAA PaCOOS Cruises

Monthly anomalies of the PFEL coastal upwelling index at 45°N, 125°W were negative from April through August 2004 (fig. 4), indicating that equatorward winds were weaker than normal through most of the upwelling season. September winds were near normal. Monthly anomalies for October and especially November were positive, indicating more upwelling and less downwelling than normal during these months. Weaker-than-average spring and summer upwelling is consistent with higher-than-average steric heights in May and June (fig. 7) and with the end-of-August values being about the same as the September average. Steric height values for November were close to normal.

Temperature sections (fig. 8) show isotherms tilting up toward the coast as normal in spring and summer, though not as steeply as usual. Surface waters were especially warm in May when inshore temperatures were more than four standard deviations above the historical average for that month (fig. 9). In November, temperatures were near normal (fig. 9).

Salinity sections (fig. 10) were similar to those observed in 2003 (Goericke et al. 2004), except that the spring and summer cruises showed fresher inshore surface waters; this inshore position of the Columbia River Plume is consistent with weaker upwelling, i.e., with weaker southward winds.

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[1] B. Sydeman, pers. comm.

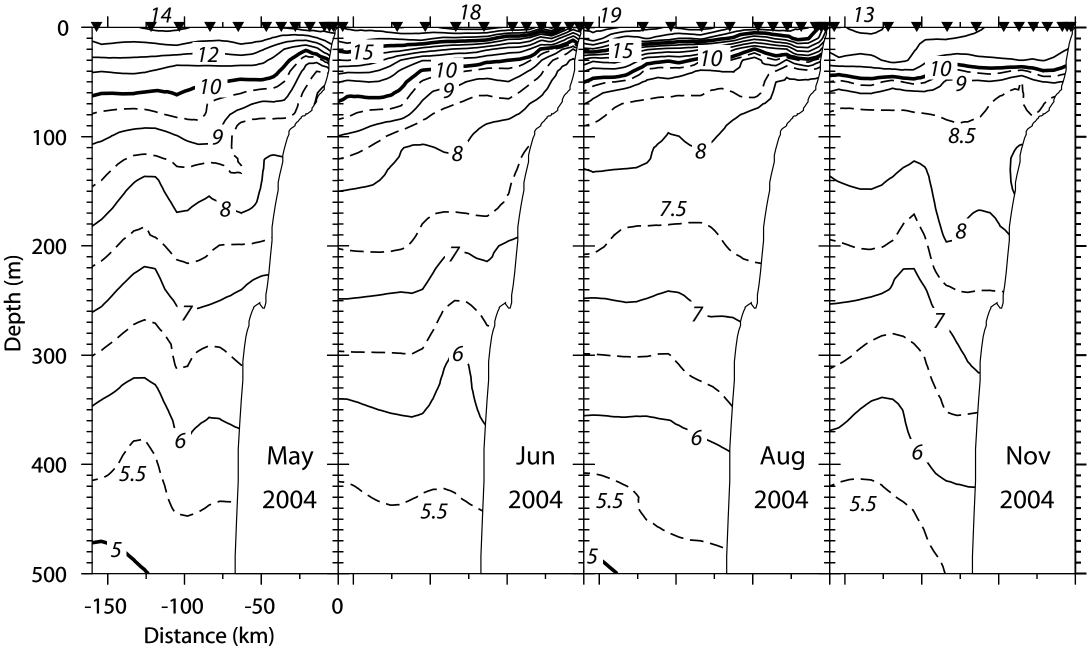

Figure 8. Temperature along the NH-line: 9–10 May, 26–27 June, 30 August–1 September, and 7–8 November 2004.

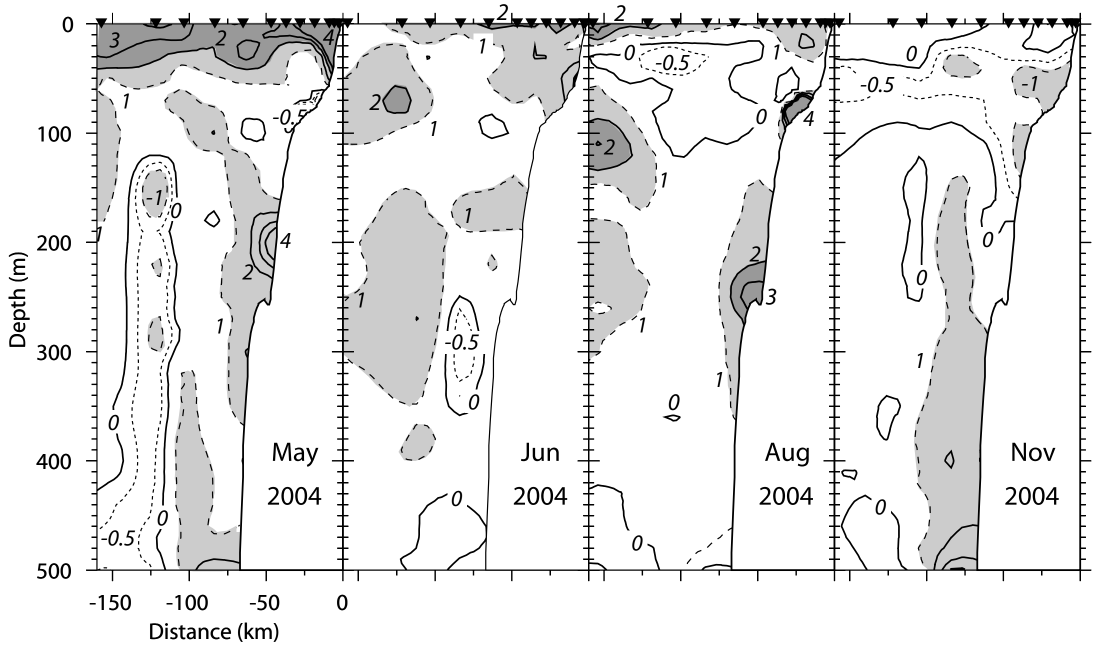

Figure 9. Normalized temperature anomalies along the NH-line, obtained by subtracting the historical monthly or seasonal average (for May, summer, September, fall) and dividing the difference by the corresponding standard deviation. (Historical values were calculated by Smith et al. 2001).

An unusually cold, nutrient-rich halocline indicating enhanced subarctic influence was present along this line in the summer of 2002 (Freeland et al. 2003; Wheeler et al. 2003). Remnants of this cold halocline anomaly were still (or again) present in summer 2003 (Goericke et al., 2004). T-S diagrams (fig. 11) for the shelf-break station NH-25 show that the halocline was not significantly colder than normal in the summer of 2004. The period of enhanced subarctic influence has apparently ended in this region. The warm (spicy) anomaly on the 25.6 kg m^{-3} isopycnal in late August likely results from local subduction of previously upwelled surface water that was exposed to solar heating. The cool, fresh (minty) anomaly in and above the halocline (S < 33.8 psu) in

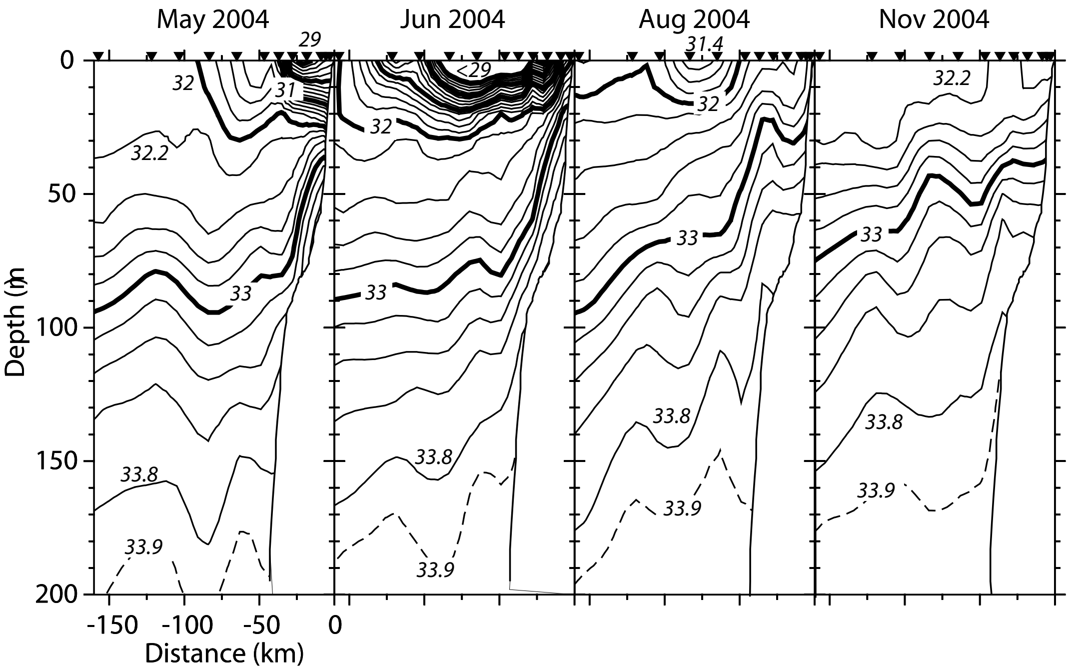

Figure 10. Salinity along the NH-line: 9–10 May, 26–27 June, 30 August–1 September, and 7–8 November 2004.

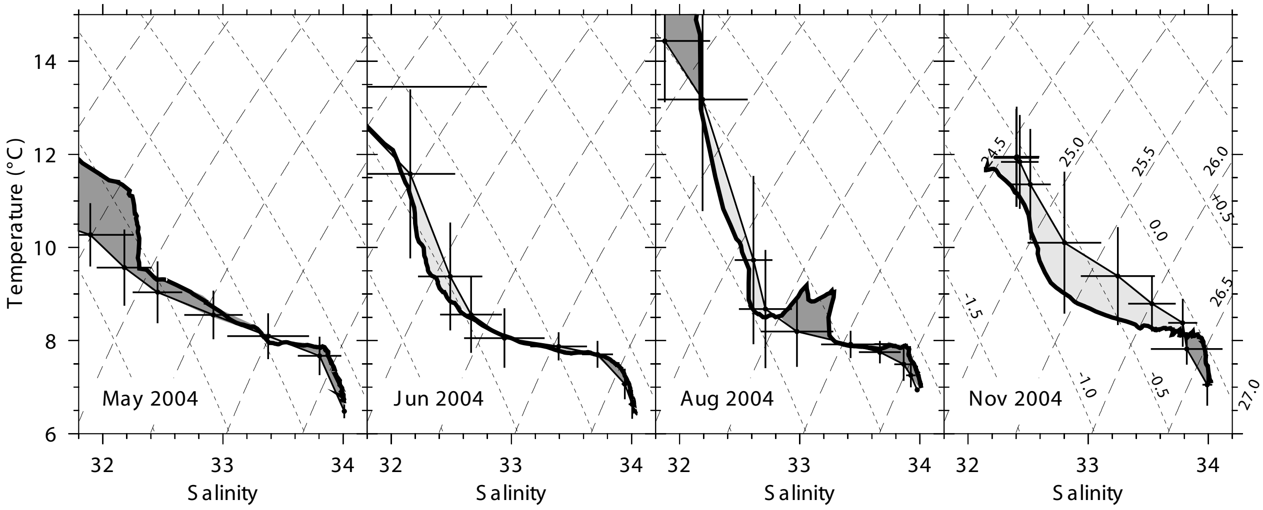

Figure 11. T-S diagrams for the shelf-break station (NH-25). Continuous curves represent CTD casts for 2004 sections; dots with bars represent 1961–71 seasonal averages and standard deviations (Smith et al. 2001).

November is likely due to the stronger-than-normal upwelling (or weaker downwelling) during autumn, which would cause the southward surface current to persist longer than normal.

Central California

Oceanographic conditions in Monterey Bay indicated that surface temperature, salinity, and nitrate were close to the 15-year mean (fig. 12). The positive anomaly of total phytoplankton biomass (chlorophyll) observed during 2004 was greater than any previous years, probably due to weaker-than-normal northwesterly winds (http://www.pfeg.noaa.gov/products/PFEL/modeled/indices/upwelling/NA/gifs/p10.gif), which reduce advective loss of phytoplankton from Monterey Bay. Positive productivity anomalies remained high but were only about one-third of the 2002–03 levels. Positive chlorophyll and productivity anomalies have now been observed continuously since 1999.

Oceanographic conditions along line 67 (out to station 90) also remained close to the climatological mean for data collected since 1997. Figure 13 shows results for

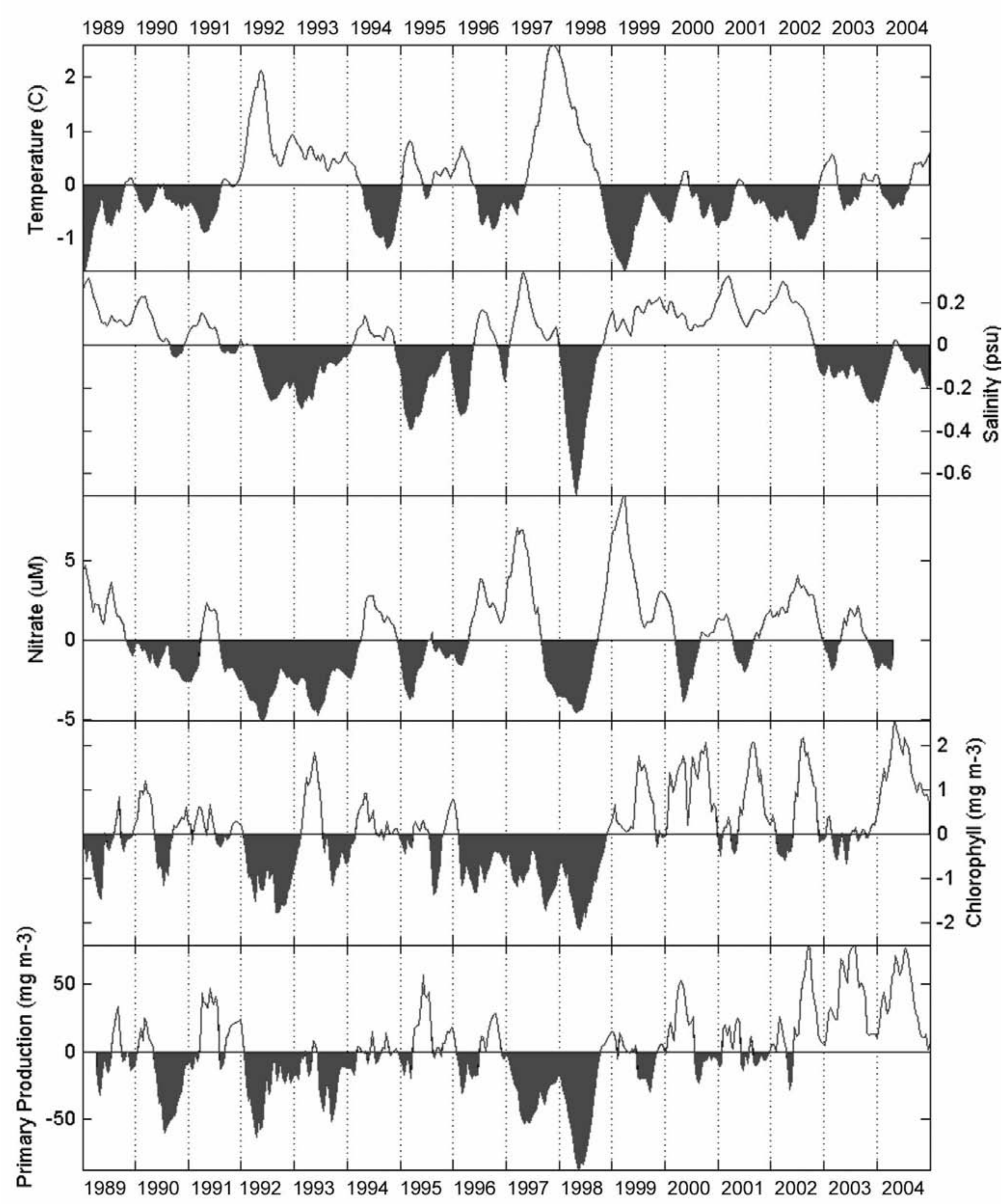

Figure 12. Anomaly plot of sea surface temperature, salinity, nitrate, chlorophyll, and primary production collected as part of the Monterey Ocean Timeseries Observatory (MOTO) program maintained by MBARI. Temperature, salinity, and nitrate were near-normal in 2004, but chlorophyll and primary production were high. As part of MOTO, three to four stations in Monterey Bay and the contiguous waters of the California Current System are sampled every three weeks. The data from all stations are averaged and the averages used to calculate a mean annual cycle. The annual mean cycle is subtracted from a smoothed time series of the data and the anomalies presented in the figure.

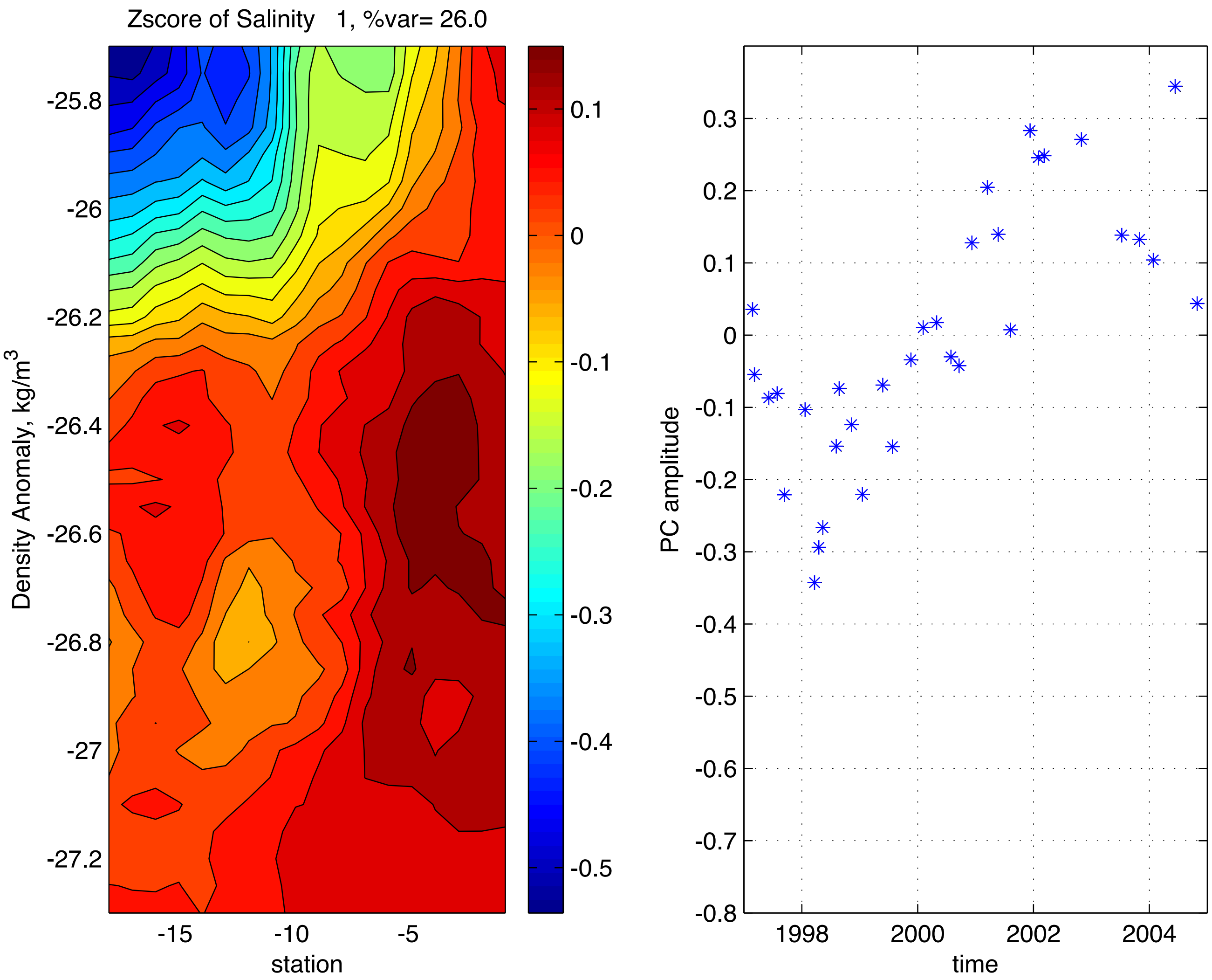

Figure 13. CalCOFI line 67 CTD sections. First principal component for salinity on density anomaly surfaces . (left) Z-score, C.I. = 0.1. (right) PC time series.

a principal component analysis of salinity on density surfaces ranging from 25.75 to 27.25 kg/m^3 for hydrographic sections that were started in 1997. The z-score has positive values associated with regions dominated by poleward flow of equatorial waters and negative values offshore for waters lighter than 26.2 kg/m^3 (also near 26.8 kg/m^3) associated with equatorward flowing subarctic (North Pacific Intermediate) waters. The first principal component accounted for 26% of the variance and steadily increased from -0.3 in 1998 to 0.3 in 2002 in a manner consistent with a decrease in salinity of subarctic waters and an increase in salinity of equatorial waters. Subsequent to 2003, this pattern appeared to reverse. The mean temperature-salinity relationship for the October 2004 section indicated that the halocline waters had warmed and the thermostad beneath the halocline was saltier than normal.

In October 2004, line 60 was occupied as well as line 67 (fig. 14). Poleward flow immediately adjacent to the shelf was observed on both transects and is reflected in the downwelling of deeper isotherms toward the coast and higher salinities over the upper slope. The strongest circulation feature observed was associated with an anticyclonic eddy, or meander, of the inshore edge of the California Current (CC) centered at the southwest corner of the grid (about 300 km from Moss Landing). Surface temperatures at this location exceeded 17°C and salinities were less than 33. The inshore edge of the anticyclonic CC feature was located about 200 km from Moss Landing and marked by vertical isohalines, in the upper 100 m, and strong convergence. Upper level currents of about 0.7 m/s were directed offshore along line 67 inshore of the front. On the offshore side of the front, currents were directed southward at about 0.4 m/s. The fresh ($S < 33$) waters above 100 m continued along line 60 to within 40 km of the Gulf of the Farallones (700 km from Moss Landing), gradually cooling to 15°C.

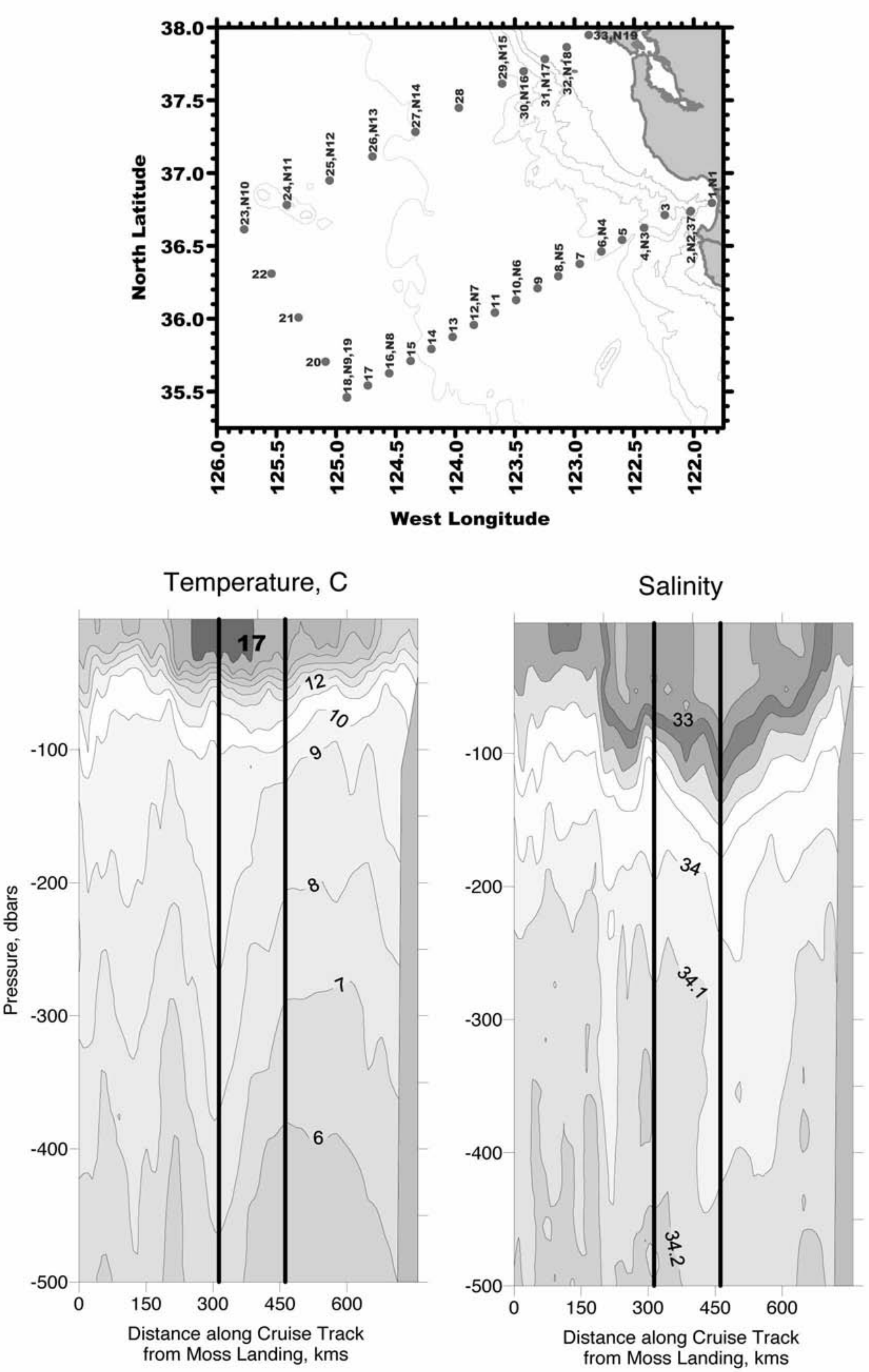

Figure 14. October 2004 Central California CalCOFI Cruise. (upper) Station pattern. (lower) Temperature and salinity plotted clockwise around the cruise track from Moss Landing (left) to Point Reyes (right). (lower left) Temperature, C.I. = 1˚C. (lower right) Salinity, C.I. = 0.2 for S > 34, 0.1 otherwise.

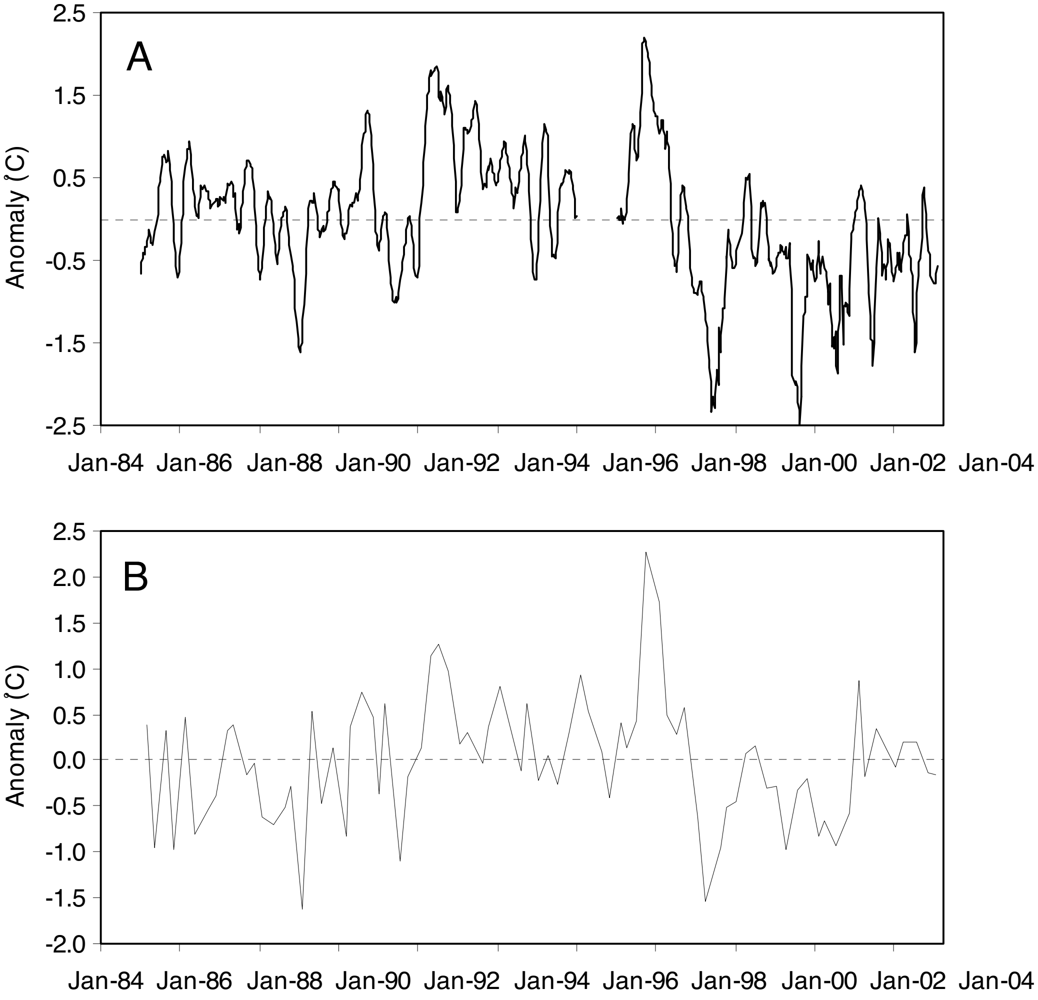

Figure 15. Average SST anomalies for the 66 standard CalCOFI stations calculated from (a) weekly AVHRR or MODIS data and (b) observations made on the quarterly CalCOFI cruises. Anomalies are calculated relative to the time period 1985 to 2004.

The deep-reaching character of the CC meander is indicated by the "V" shape of the isotherms which extended to pressures greater than 1000 dbars directly under the 17°C surface warm pool (300 km from Moss Landing). Along line 60, beginning at a distance of 450 km from Moss Landing, isopycnals below 200 dbar continued to rise toward the coast to within a distance of 30–60 km from the slope. The upward slope toward the coast indicates equatorward flow and was also marked by S = 34.1 waters extending to pressures of 400 dbar. Note that these waters were also found along line 67 directly under the surface front noted above at a distance of 200 km from Moss Landing.

Southern California Bight: CalCOFI Survey Cruises

Overview: Over the last year, CalCOFI conducted the usual four cruises in April, July, November of 2004, and January of 2005. Results from these cruises will be presented here and contrasted with those from previous years and compared to the climatologies. Average remotely sensed SST (SST$_{\mathrm{MODIS}}$; fig. 15a) at the 66 standard CalCOFI stations were similar to average in situ SST measured at the stations (SST$_{\mathrm{CalCOFI}}$; fig. 15b). Anomalies of SST$_{\mathrm{CalCOFI}}$ over the last year were close to zero; in contrast, anomalies of SST$_{\mathrm{MODIS}}$ were 0.5°C below normal, suggesting that the quarterly sampling introduced some bias. This is supported by the similar average temperatures for the differing base periods—SST$_{\mathrm{MODIS}}$: 85–05 and SST$_{\mathrm{CalCOFI}}$: 84–05 (16.09 and 16.16°, respectively).

Mixed layer depths (MLD) during the last year were slightly below the long-term average (fig. 16a), similar to values observed since 2002. ML temperature anomalies (fig. 16b) were virtually identical to SST$_{\mathrm{CalCOFI}}$ anomalies. Annual averages of these have been close to zero after a period of negative values from 1999 to 2002.

ML salinities continue to be abnormally low (fig. 16c).

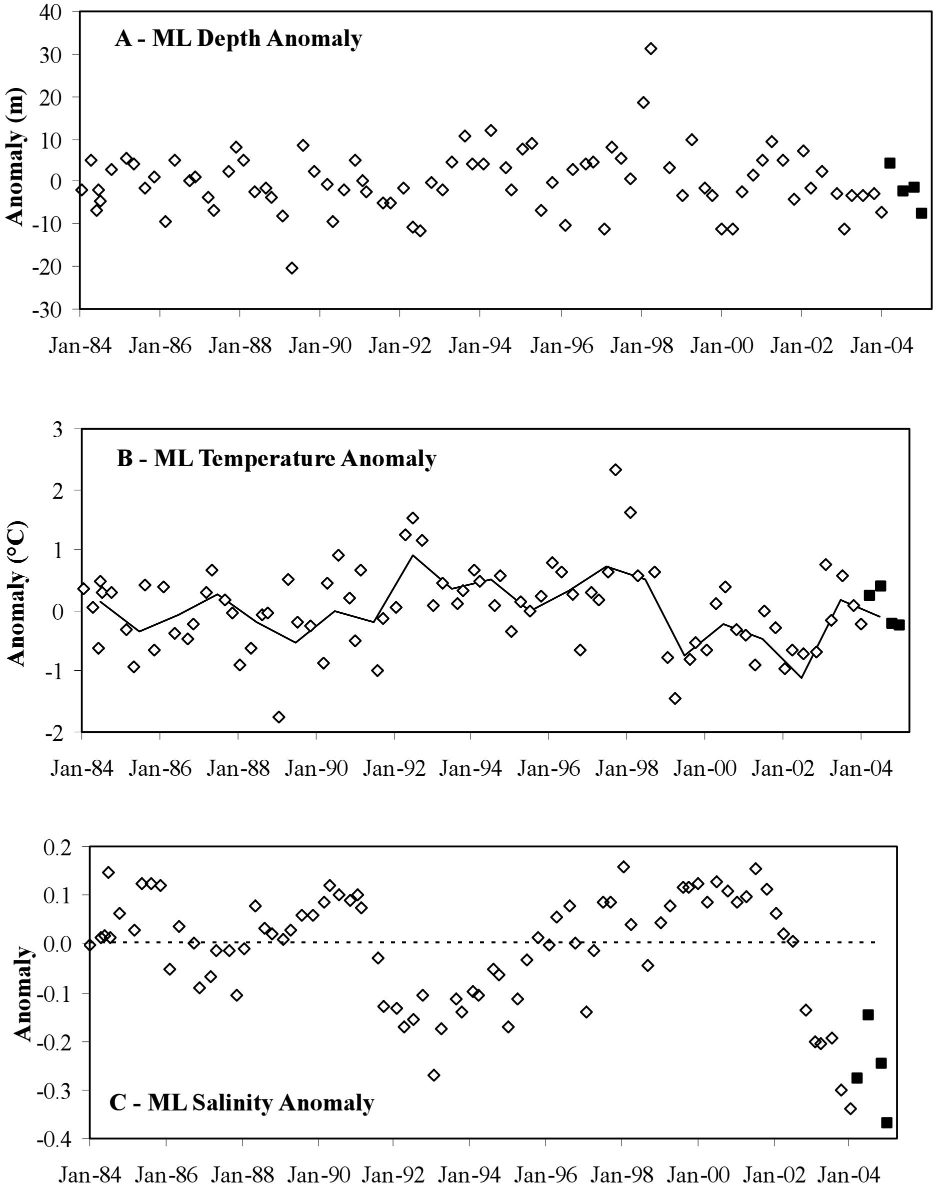

Figure 16. CalCOFI region anomalies for (a) mixed layer depth (MLD), (b) mixed layer temperature, and (c) mixed layer salinity. Data are derived from all 66 standard CalCOFI stations (fig. 1). Open symbols are for the period 1984 to spring of 2003. Data from the last four cruises are plotted as solid symbols. Annual averages in panel (b) are indicated with a solid line.

Average anomalies of these, 0.26 over the last year, were similar to those observed during the prior year (0.26). These anomalies are found throughout the CalCOFI region (e.g. fig. 17). Anomalies over the last two years were largest at the edge of the Central Gyre, becoming weaker, but still distinct, in the inshore areas (fig. 17). These anomalies are confined to the mixed layer and the seasonal thermocline.

0404 (23 Mar.–8 Apr. 2004; fig. 18). Preliminary data for this cruise were presented in last year's report (Goericke et al. 2004). The surface current patterns during April, as indicated by the dynamic height anomaly map, show two separate bands of strong southward flow, much like those seen during the spring of 2003 (Venrick et al. 2003). The strong flow starting at the northwest corner of the map was the main core of the California Current Jet, as revealed by the low salinity water that is commonly associated with the fastest part of the current. The other strong southward current band closer to shore was adjacent to the strong upwelling zone north of Point Conception. The upwelling is revealed by the cool temperatures and relatively high salinity seen near Point Conception. The cruise mean 10 m temperature was slightly warmer than normal. Near-surface

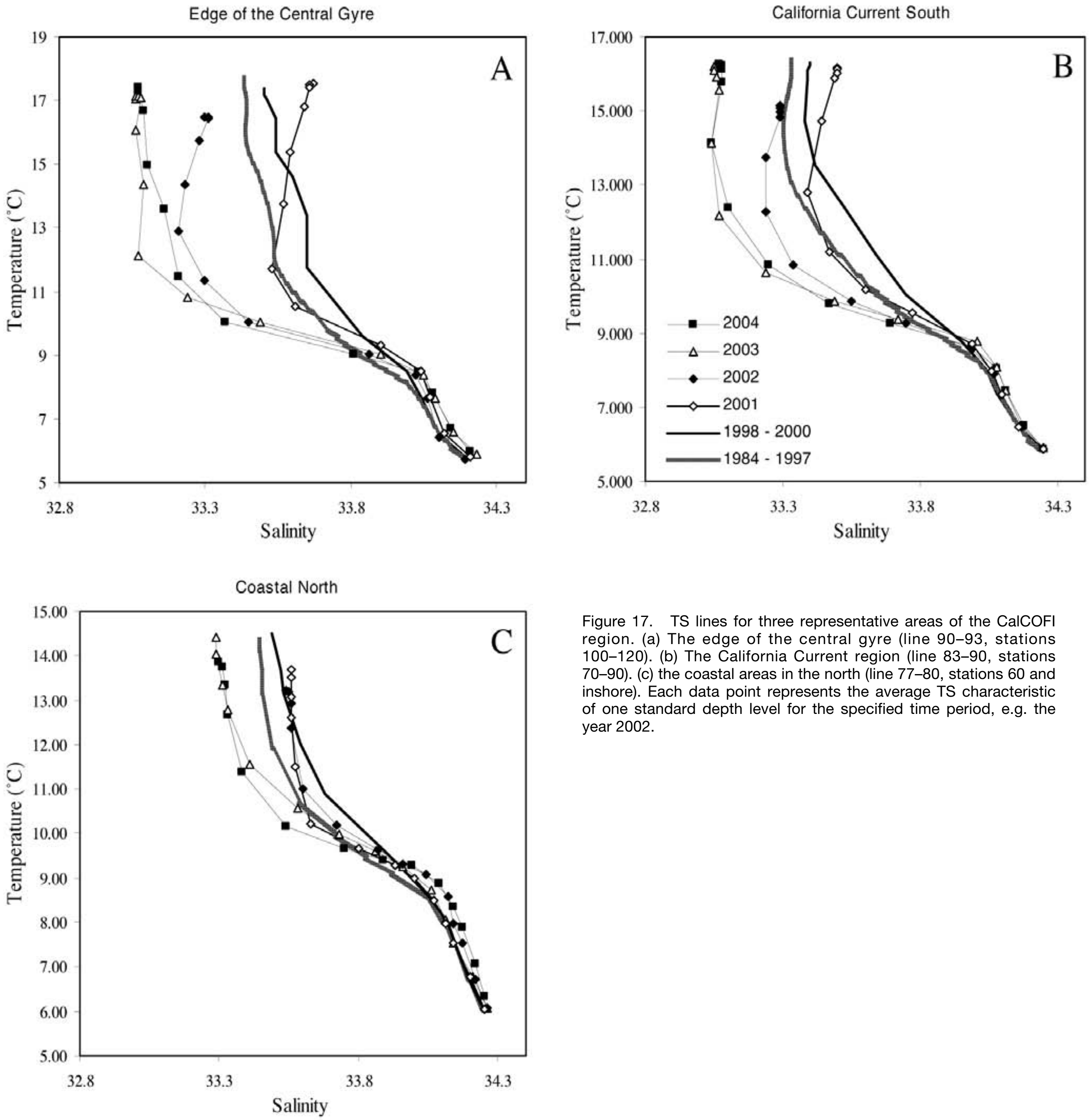

Figure 17. TS lines for three representative areas of the CalCOFI region. (a) The edge of the central gyre (line 90–93, stations 100–120). (b) The California Current region (line 83–90, stations 70–90). (c) the coastal areas in the north (line 77–80, stations 60 and inshore). Each data point represents the average TS characteristic of one standard depth level for the specified time period, e.g. the year 2002.

chlorophyll-*a* concentrations were also very high near the nutrient rich upwelled water. Offshore of the main California Current Jet, chlorophyll *a* was quite low, as usual. The Southern California Eddy was small at this time and was confined to the area around the northern Channel Islands.

0407 (13–28 Jul. 2004; fig. 19). The California Current Jet seen far offshore in the spring (0404) cruise had split into two branches by summer time with an anticyclonic eddy embedded between the two flows. The cyclonic Southern California Eddy had expanded in size and was centered offshore of the Channel Islands, with northward coastal flow up to the Santa Barbara Basin. Low 10 m salinity was associated with the main California Current Jet, and high saltiness occurred in the shoreward portion of the cruise pattern. Overall, however, the cruise mean 10 m salinity remained well below normal.

The temperature at 10 m was high both in the offshore regions and in the southeast corner of the pattern, between San Diego and the Channel Islands. Cool temperatures were seen extending southward from Point

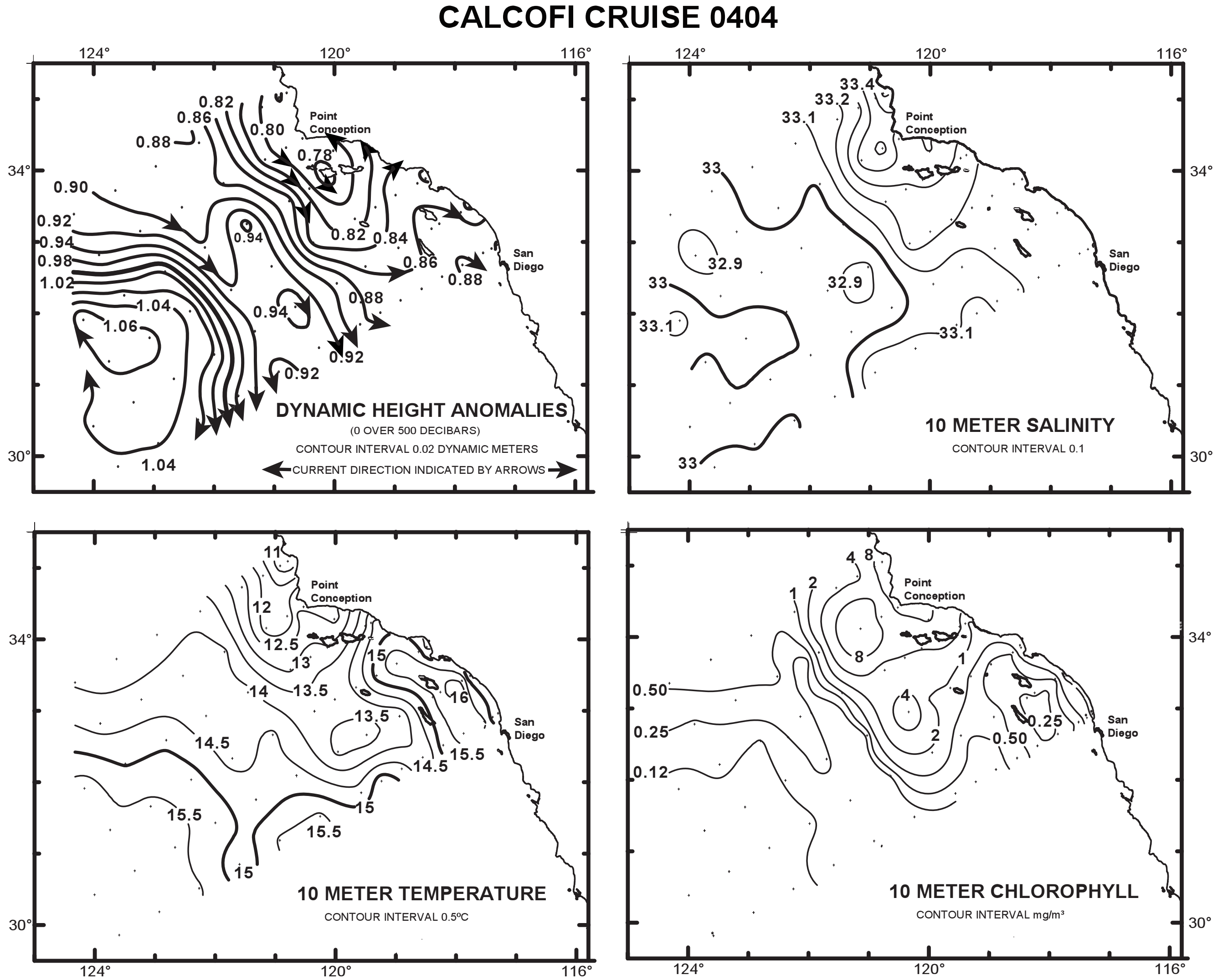

Figure 18. Spatial patterns for CalCOFI cruise 0404, including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll *a*.

Conception, all the way through the cruise pattern, and located just inshore of the strong southward flow. Elevated salinities were found in the same zone. Together, these are indications of upwelling, corroborated by measurements taken at station 83.51, next to Santa Rosa Island, with surface oxygen saturation of only 88% and nitrate concentrations of 7.8 µm.

Surface chlorophyll *a* was unusually high for a summer cruise, especially around Point Conception, in the Santa Barbara Basin, and on the shallow shelf stations close to shore. The dissolved oxygen saturations on the shelf stations (between lines 83 and 93) were highly oversaturated, ranging from 120 to 148%, which indicates an accumulation of oxygen from an ongoing phytoplankton bloom.

0411 (13–28 Jul. 2004; fig. 20). Strong southward surface flow on this fall cruise was found between stations 90 and 100 on all six station lines, with little variation or meandering. An arc of relatively strong northward flow was seen along the coast to beyond Point Conception. Flows were weak over the middle of the pattern. The lowest 10 m salinities were observed in the core of the California Current Jet, where salinity anomalies were −0.5. The 10 m temperature anomaly was lowest near Point Conception, but the overall cruise mean was slightly warmer than normal, although the California Current Jet carried water that was slightly cooler than normal.

Chlorophyll-*a* concentrations at 10 m were elevated near Point Conception, otherwise, they were generally low, as is typical for an autumn cruise. Observed shelf station dissolved oxygen saturation was closer to the normal over-saturation levels (105%).

0501 (4–20 Jan. 2005; fig. 21). Some features of the

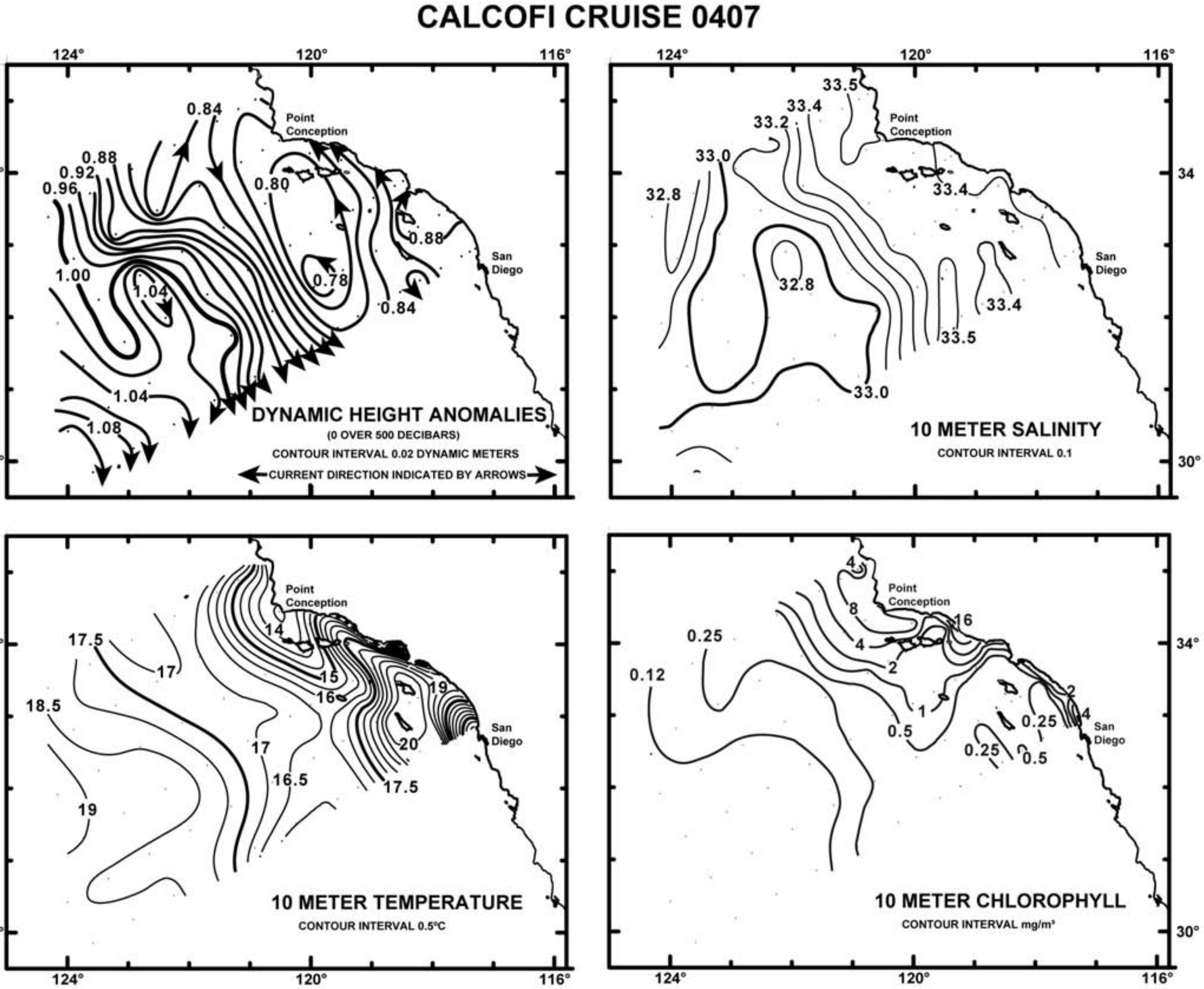

Figure 19. Spatial patterns for CalCOFI cruise 0407, including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll-*a*.

surface flow patterns for the 0501 winter cruise were similar to those of cruise 0411: the California Current Jet was still strong, located at the outer edge of the cruise pattern, and the northward coastal flow had intensified. However, other features appeared that were more like the flow seen in last year's winter cruise (0401): an eddy centered on station 80.70 and a large current loop penetrating shoreward along line 90.

Low salinities were seen in the offshore jet and in the shoreward current loop along line 90. There was considerable rainfall in Southern California this winter with significant runoff. This was probably responsible for the low surface salinities observed in the near-shore areas. Shipboard observers also noted high turbidity and suspended material in the upper meter at some stations. The 10 m temperatures were slightly above average for the cruise, especially at the eastern half of the pattern, but stations in the California Current Jet were slightly cooler than normal.

Over most of the pattern, chlorophyll *a* at 10 m was quite low, and surface dissolved oxygen was at equilibrium with the atmosphere with saturation values around 99 to 101%. Both patterns are typical of winter. A few stations were slightly under-saturated either due to winter convective overturn or upwelling at some stations.

Station 90.28 showed some unusual characteristics resulting from local runoff. The surface salinity was very low, 28.4, and the nutrient profile had an "inverted" shape with the highest nutrients appearing in the surface, low-salinity layer and lower nutrients below. Surface chlorophyll *a* was relatively high at this station, and the dissolved oxygen was over-saturated by 26%.

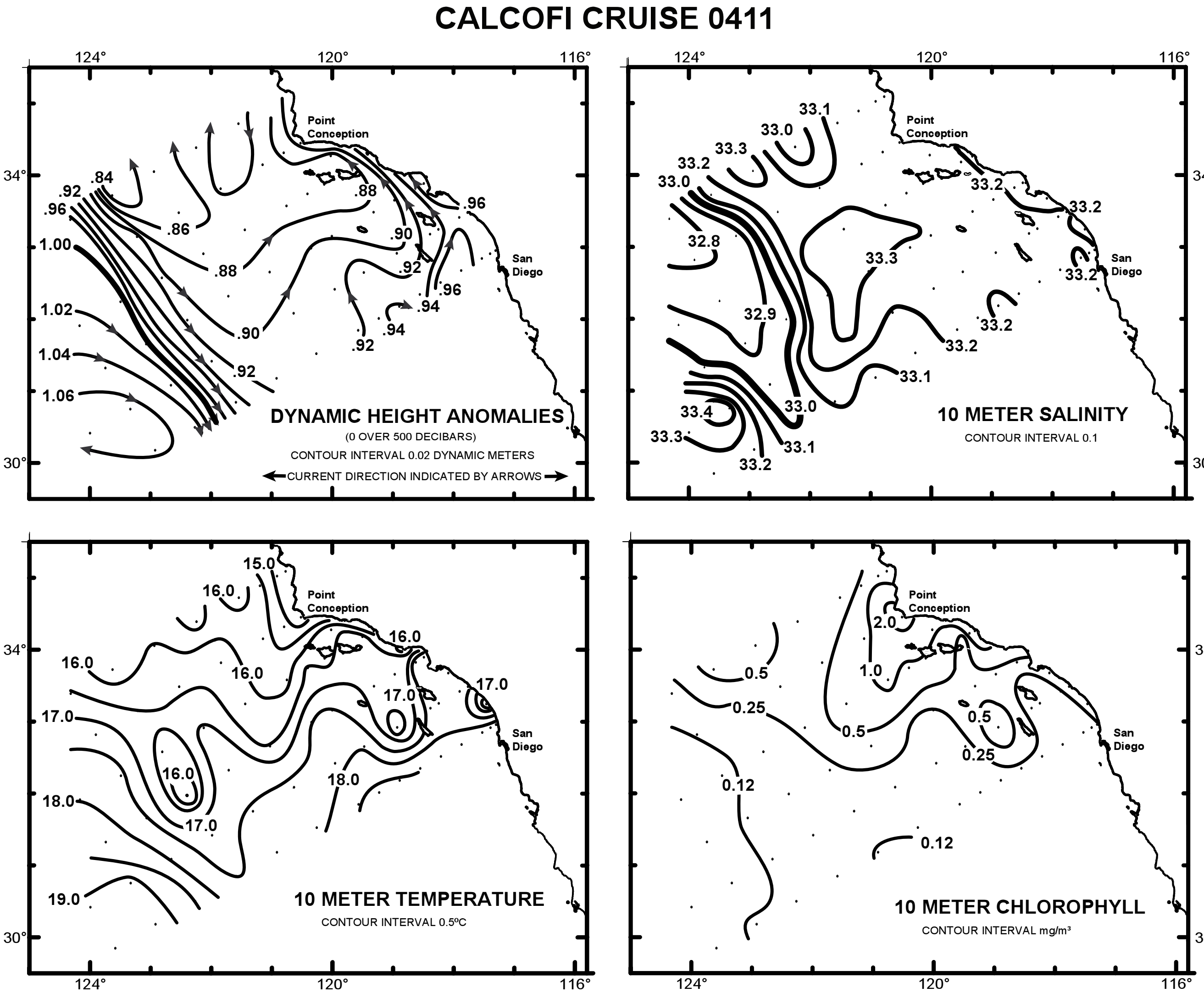

Figure 20. Spatial patterns for CalCOFI cruise 0411, including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll-*a*.

IMECOCAL Survey Cruises off Baja California

The IMECOCAL program surveyed the CCS off Baja California during April, July, October 2004, and January 2005. During all four cruises, upper ocean salinities ($\sigma_t < 25.5$) were significantly lower than climatological means (fig. 22), patterns similar to those observed off Baja California during the weak El Niño of 2002–03 (Durazo et al. 2005) and off Southern California during 2002 to 2004 (Goericke et al. 2004). These upper layer salinity anomalies were first evident in 2002/03 in the upper thermocline ($\sigma_t < 24.5$) and later expanded further ($\sigma_t < 25.5$). These anomalies were still evident in January 2005 (fig. 22). SST anomalies were only positive during the winter and spring of 2004 (cruises 0301 and 0304, respectively).

0404 (15 Apr.–7 May 2004; fig. 23). The dynamic height anomalies during the spring showed the CC as a very uniform band close to the coast flowing SSE. The current entered the survey region both from the northernmost section and from the northwest. Near shore, low temperatures and relatively high values of chlorophyll *a* suggest upwelling, with maximum chlorophyll-*a* concentrations inside Bahía Vizcaíno and south of Punta Eugenia. Relatively low salinities were found throughout the survey area. The core of the CC closely followed the salinity minimum of 33.2. Salinities above the $\sigma_t < 25.5$ surface were lower than the climatological mean (fig. 22).

0407 (9–29 Jul. 2004; fig. 24). Dynamic height anomalies during July 2004 suggest that the CC entered the survey region between lines 100 and 103 in the form of a clockwise meander, left the survey region, reentered the region at 27 to 28°N, meandered and flowed southward close to the coast. Lower coastal temperatures sug-

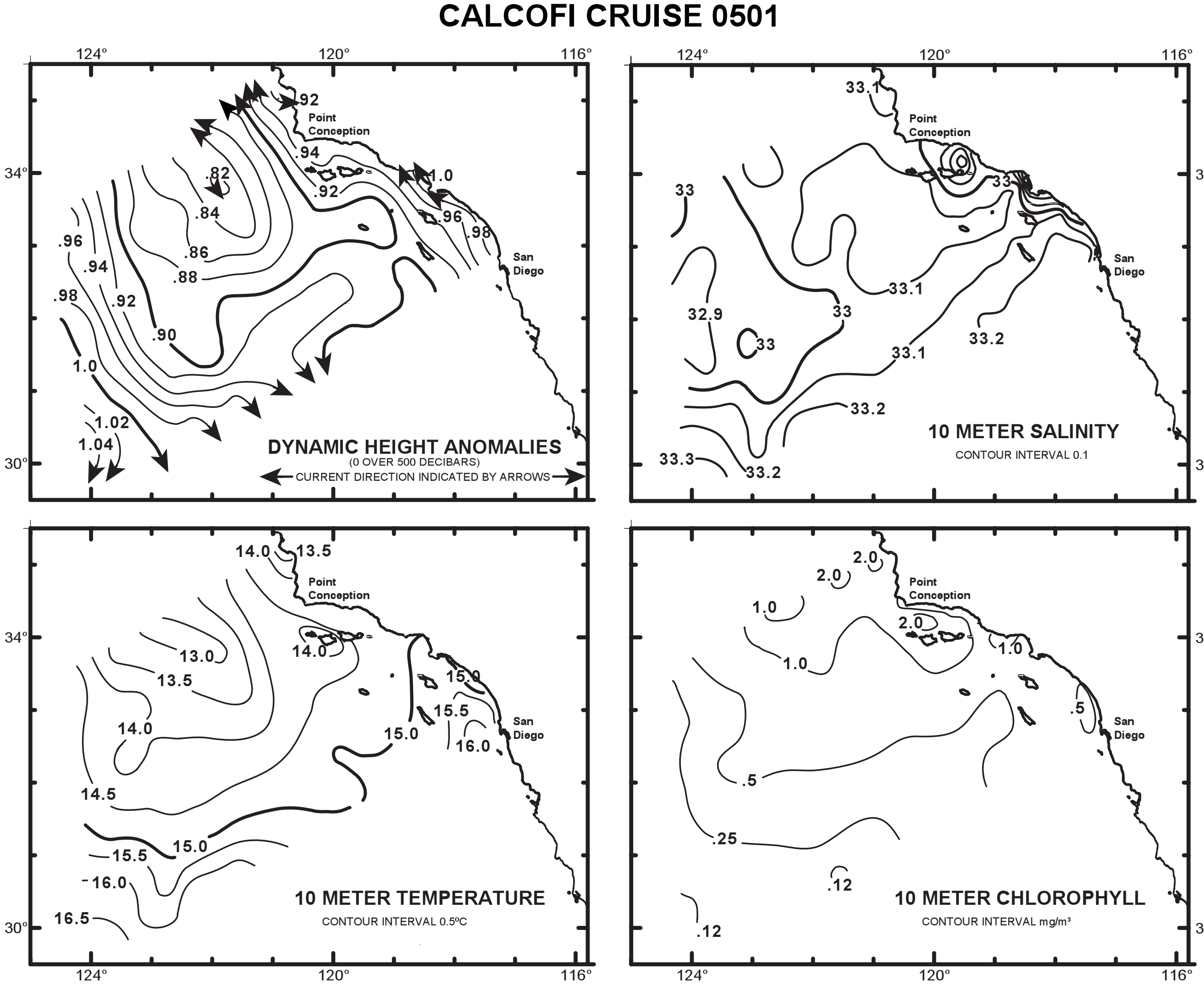

Figure 21. Spatial patterns for CalCOFI cruise 0501 including upper-ocean geostrophic flow estimated from the 0/500 dbar dynamic height field, 10 m salinity, 10 m temperature, and 10 m chlorophyll-*a*.

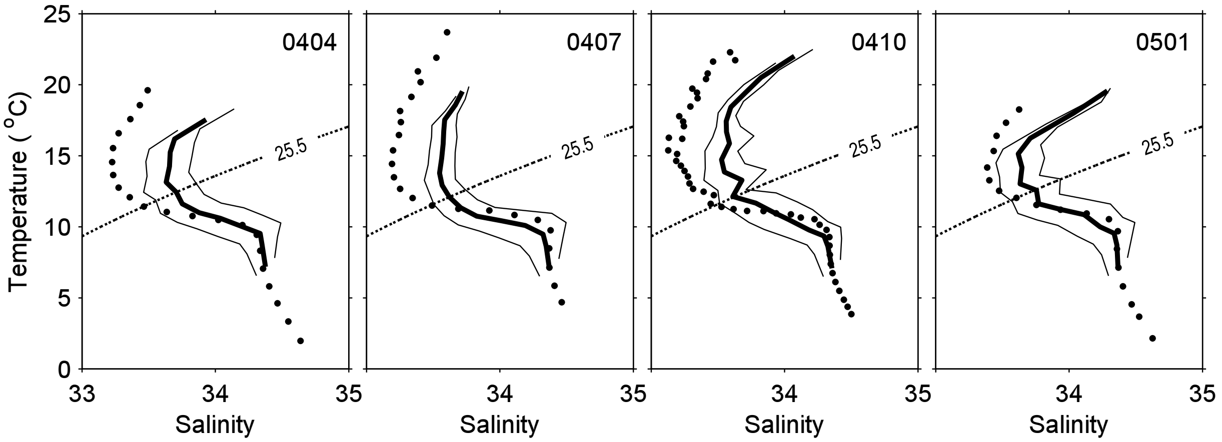

Figure 22. Temperature-salinity diagrams for the spring, summer, and fall 2004 and winter 2005 data collected in the IMECOCAL grid. Bold continuous line represents the climatological mean computed at standard depths from historical (1948–78) and recent (1997–2004) data sets, from 0 to 500 m. Continuous thin lines depict one standard deviation along the salinity axis. Heavy dots indicate the mean temperature-salinity for each cruise. Both cruise and climatological mean profiles were obtained using the same stations on each case. Thin dotted line marks the $\sigma t = 25.5$ isopycnal contour.

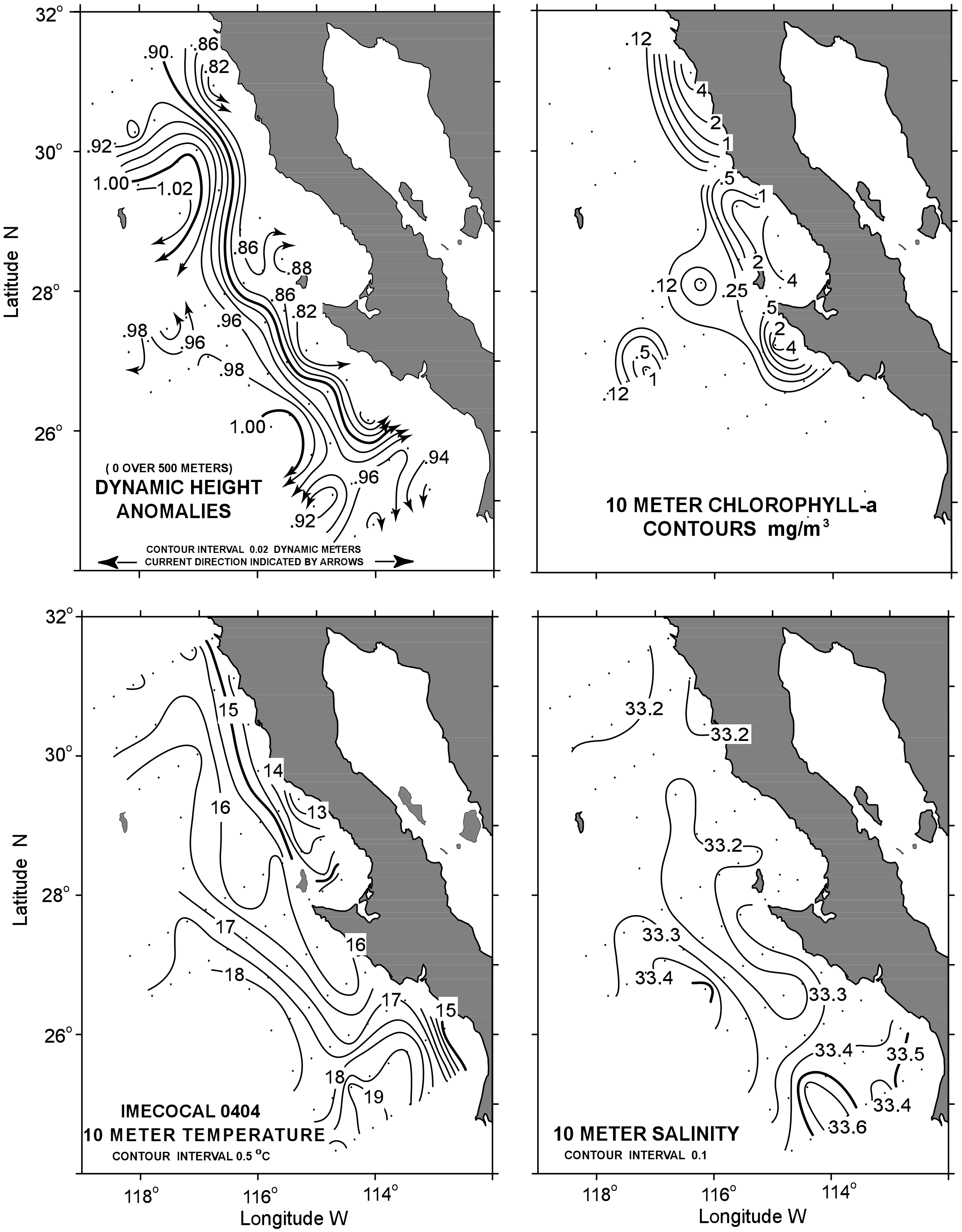

Figure 23. Spatial pattern for the IMECOCAL cruise 0404 (15 Apr.–7 May 2004) including upper ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll, 10 m temperature, and 10 m salinity. Full data of chlorophyll-*a* are not available for this cruise because some stations were missed due to bad weather.

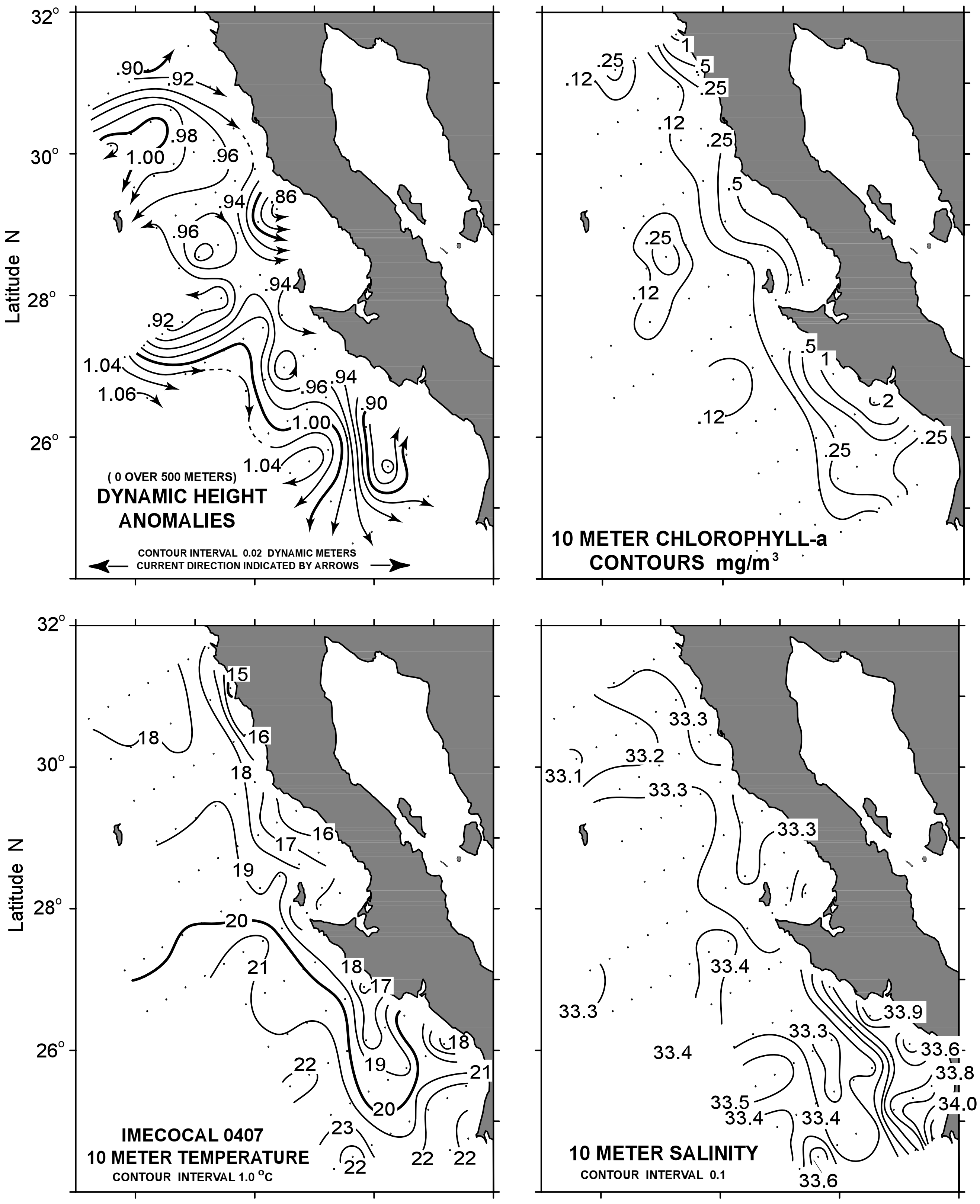

Figure 24. Spatial pattern for the IMECOCAL cruise 0407 (9–29 Jul. 2004), including upper ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

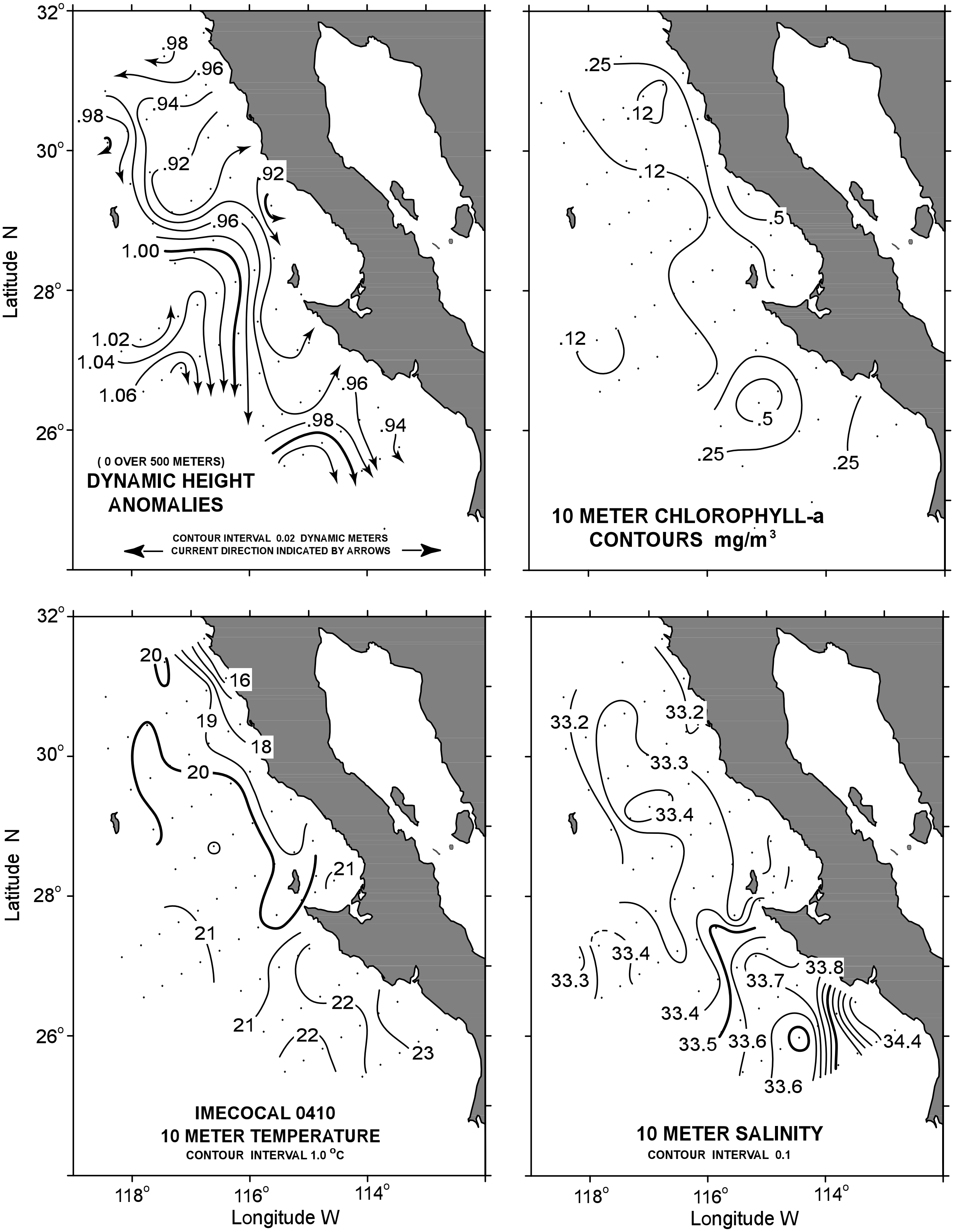

Figure 25. Spatial pattern for the IMECOCAL cruise 0410 (9–28 Oct. 2004), including upper ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

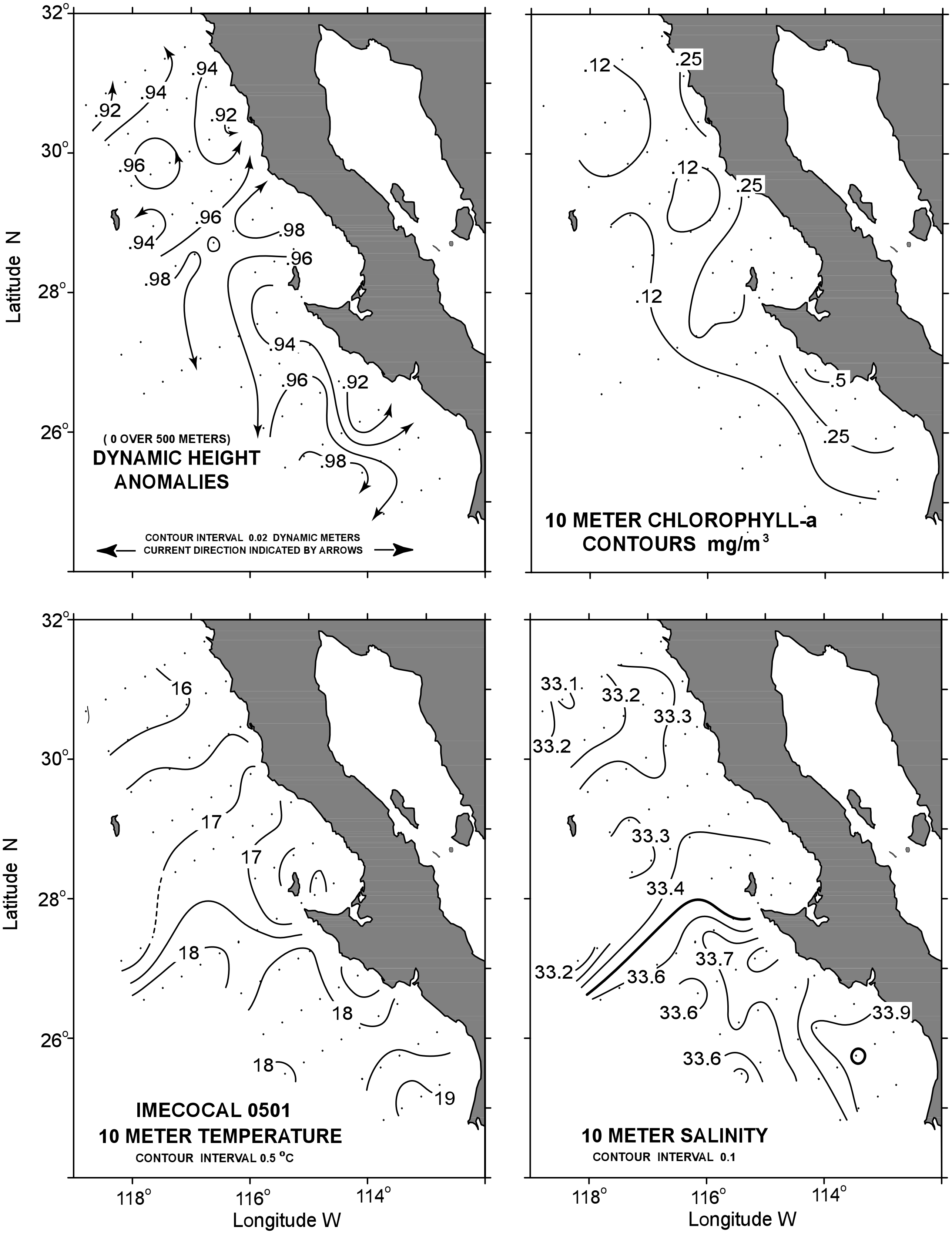

Figure 26. Spatial pattern for the IMECOCAL cruise 0501 (21 Jan.–11 Feb. 2005), including upper ocean geostrophic flow estimated from 0/500 dbar dynamic height field, 10 m chlorophyll, 10 m temperature, and 10 m salinity.

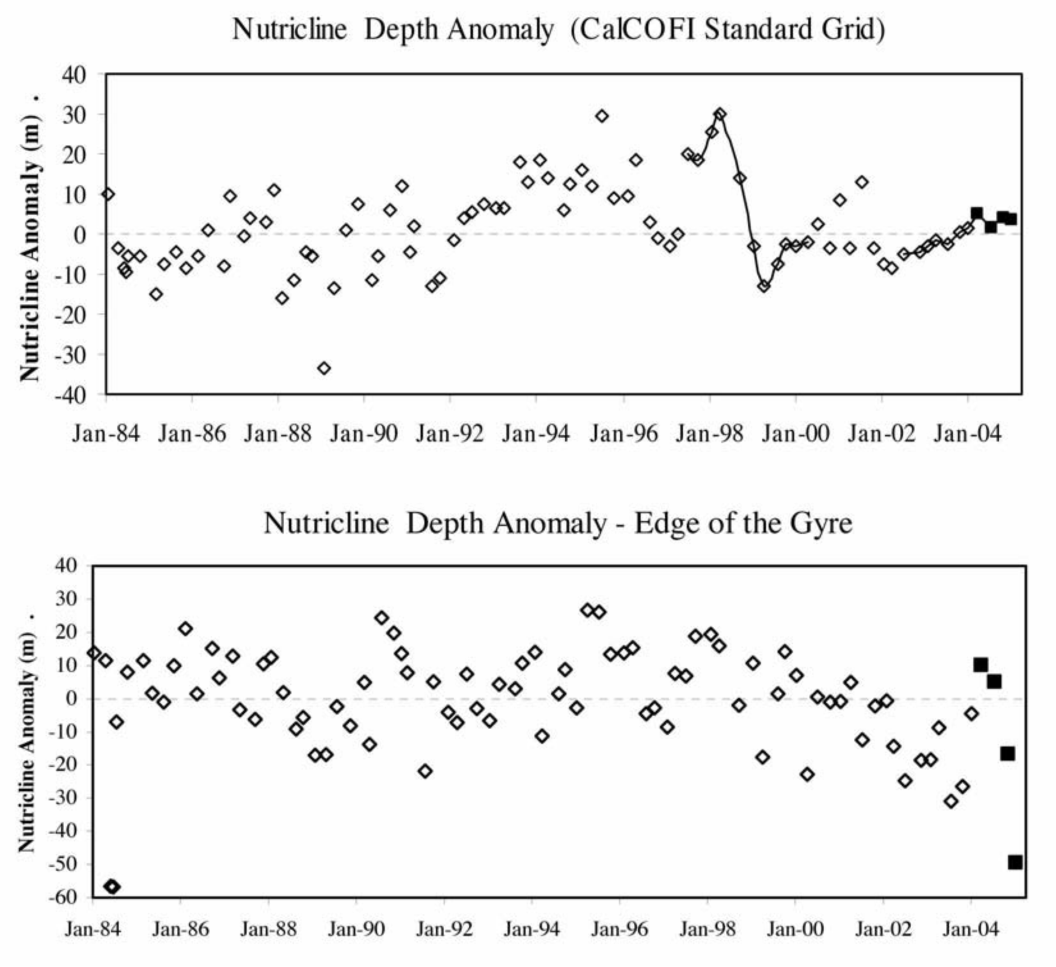

Figure 27. CalCOFI region anomalies for nutricline depth. (a) CalCOFI area anomalies, (b) anomalies for the edge of the central gyre (Line 90–93, Stations 100–120). Data and symbol codes are the same as those in Figure 16.

gest upwelling, mainly south of the coastal promontories, Ensenada to Colonet (30.5–31°N), Punta Baja (29°N), and Punta Eugenia (27°N). Surface salinities were near uniform in the northern portion of the region but showed large gradients south of Punta Eugenia. Higher salinities near the coast suggest a poleward flow of water from the south. Lower than normal salinities were observed above the σ_t = 25.5 surface, consistent with observations made during the previous cruise. Concentrations of chlorophyll-*a* were very low over most of the survey region (<0.25 µg/L), with the exception of upwelling centers along the coast south of Punta Eugenia (>1 µg/L).

0410 (9–28 Oct. 2004; fig. 25). Low gradients of dynamic height anomalies north of 29°N suggest that the core of the CC was located west of the sampling area. The CC core appears to have entered the survey region at the northwestern corner and meandered southward roughly along stations 60 to latitude 29°N. South of this latitude, it flowed closer to shore. South of Punta Eugenia, the CC core was displaced offshore by water of southern origin (S > 33.6). With the exception of the coastal region south of Ensenada, where upwelling may have occurred, 10 m temperatures were relatively high throughout the study domain, although these were near the seasonal mean (fig. 22). 10 m salinities were relatively uniform and low north of 28°N, but had strong gradients and higher values south of 28°N. Near surface waters (σ_t < 25.5) were found fresher than the mean. Chlorophyll-*a* concentrations were very low throughout the survey region.

0501 (21 Jan.–11 Feb. 2005; fig. 26). Gradients of dynamic height anomalies north of 28°N during January-February 2005 were small and suggested flow towards the coast between lines 100 and 103 and lines 110 and 113. South of 28°N, flows toward the south appeared more organized although dynamic height gradients were small. Chlorophyll-*a* concentrations were relatively low. Temperature contours followed those of dynamic height, i.e., an east-west orientation. Salinity contours were generally perpendicular to the coast, with a latitudinal gradient of ΔS ~1 along the north and south extremes of

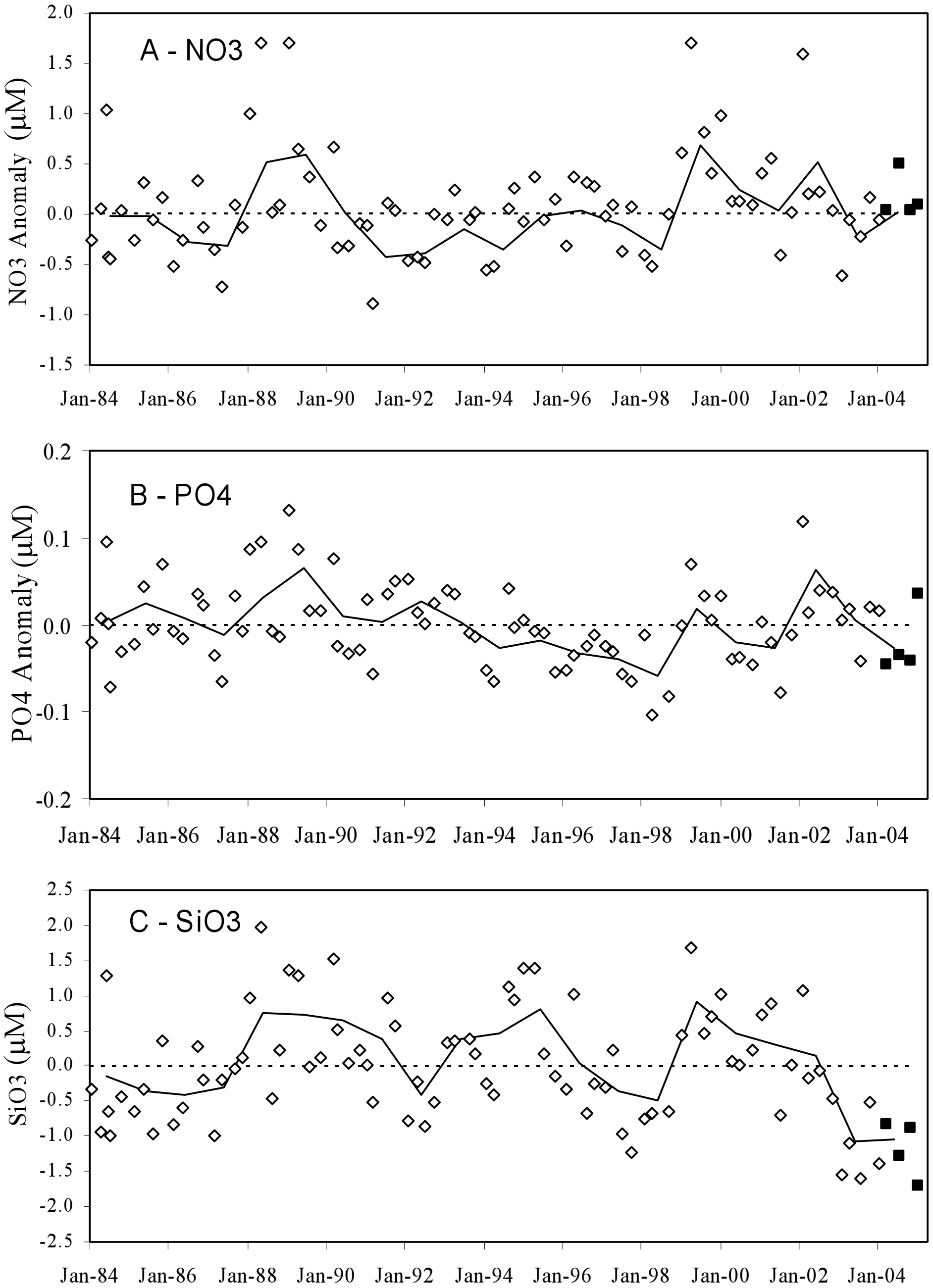

Figure 28. CalCOFI region anomalies for concentrations of (a) nitrate, (b) phosphate, and (c) silicate in the mixed layer. Data and symbol codes are the same as those in Figure 16.

the survey region. For this cruise, the T-S diagram indicates near-normal temperatures but lower than the mean salinities (fig. 22).

BIOLOGICAL PATTERNS AND PROCESSES

Macronutrients and Chlorophyll *a*

Oregon: The 2002–03 enhanced subarctic influence coincided with a significant increase in phytoplankton biomass (Wheeler et al. 2003). In July 2002, July 2003, September 2002, and September 2003, values of spatially-averaged, vertically-integrated chlorophyll in this region were 126, 232, 70, and 89 mg m^{-2}, respectively (Goericke et al. 2004). In contrast, the value for late August 2004 (the only cruise for which we have recent data) is 43 mg m^{-2}, which is similar to the September values observed in earlier LTOP years (1998–2001). This reduction in phytoplankton biomass seems to confirm that the period of enhanced subarctic influence has ended.

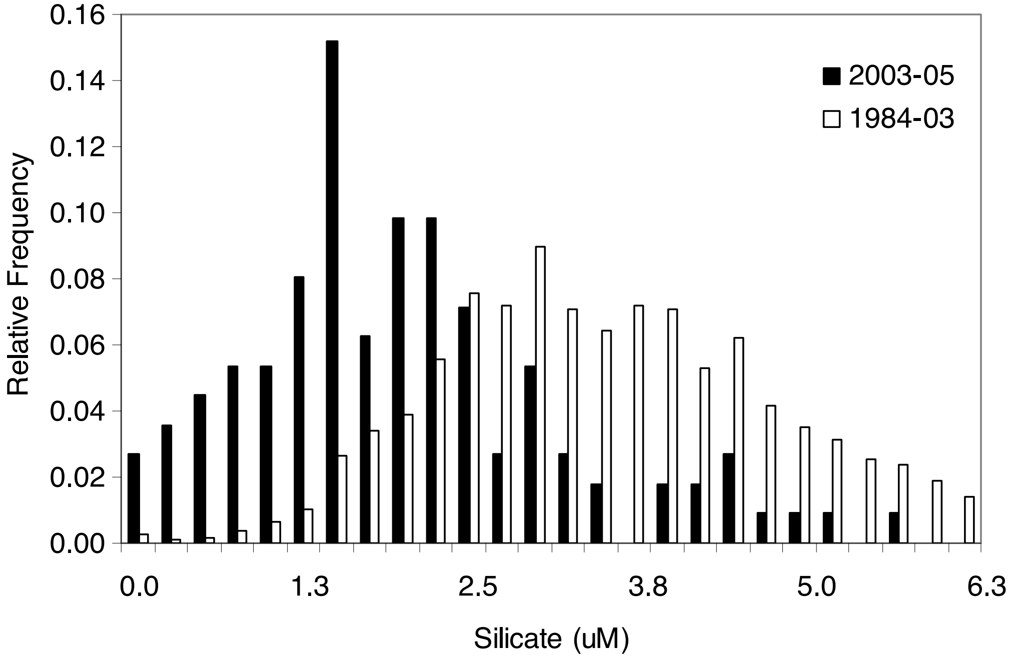

Figure 29. Normalized ML silicate concentration frequencies for CalCOFI stations with nitrate concentrations larger than 0.3 µM.

CalCOFI: Nutricline depth anomalies for the whole CalCOFI region were close to zero over the last year (fig. 27a), similar to the previous year. This pattern, however, was not seen throughout the CalCOFI area; large negative nutricline anomalies—i.e. nutriclines shallower than normal—were observed in the offshore regions in the fall and winter (fig. 27b). Mixed layer (ML) nitrate and phosphate anomalies were variable but, when averaged over the year, close to zero (fig. 28a, b). Silicate anomalies observed over the last two years are the lowest on record (fig. 28c). These large negative silicate anomalies coincided with the large negative salinity anomalies, suggesting that the former, too, are directly or indirectly related to the possible increased transport of subarctic waters into the CalCOFI area. These changes in silicate concentrations may affect diatom growth. The half saturation constant for silicate uptake by most diatoms is in the range of 2 to 3 µM. Prior to 2003, only 9% of all stations with ML nitrate concentrations larger than 0.3 µM had silicate concentrations <2.5 µM (i.e. were likely to be limited by silica rather than nitrate), but after 2003, 52% of all stations were in that category (fig. 29). For comparison, during 1984 to 1987, when silicate concentrations were also consistently below their climatological average, this value was 19%. These data imply that the likelihood that diatom growth was limited in recent years by the availability of silicate increased by about a factor of five.

Last year the Santa Barbara Basin (SBB) was in an unusual state as well. The basin is surrounded by a sill; its deeper regions are isolated from the surrounding ocean. It flushes only intermittently. At these times, cold, oxygen- and nitrate-rich waters replace the older oxygen- and nitrate-depleted waters. Oxygen concentrations in the Santa Barbara Basin often reach suboxic levels (fig. 30a), initiating denitrification. During 2004, nitrate dropped below values of 15 µM, the lowest observed since measurements began in 1984 (fig. 30b). In January 2005 values were less than 1 µM. Concentrations of nitrite, which had previously always been less than 0.2 µM, reached values of 2.9 µM in July 2004 (fig. 30c). Rates of nitrate consumption at the bottom of the basin over the last 18 months were 0.060 µm day^{-1}. This value is similar to those previously observed, 0.058 ± 0.016 µm day^{-1} ($n = 10$). However, previously denitrification occurred continuously only over periods of 3 to 6 months, interrupted by partial or complete flushing of the basin. These data suggest that the drawdown of nitrate in the basin is simply due to changing hydrographic forcing of the basin. However, the dramatic increase in concentrations of nitrite at the bottom of the basin (fig. 30c) suggests that a consequence of this hydrographic forcing was a change in some biogeochemical processes within the basin.

The annual average of the CalCOFI-domain chlorophyll *a* was close to the 1999–2003 average value. Values observed during the spring were not as high as those observed during some previous years since 1998. This, however, may have been a function of the timing of the cruise. The standing stocks observed during the sum-

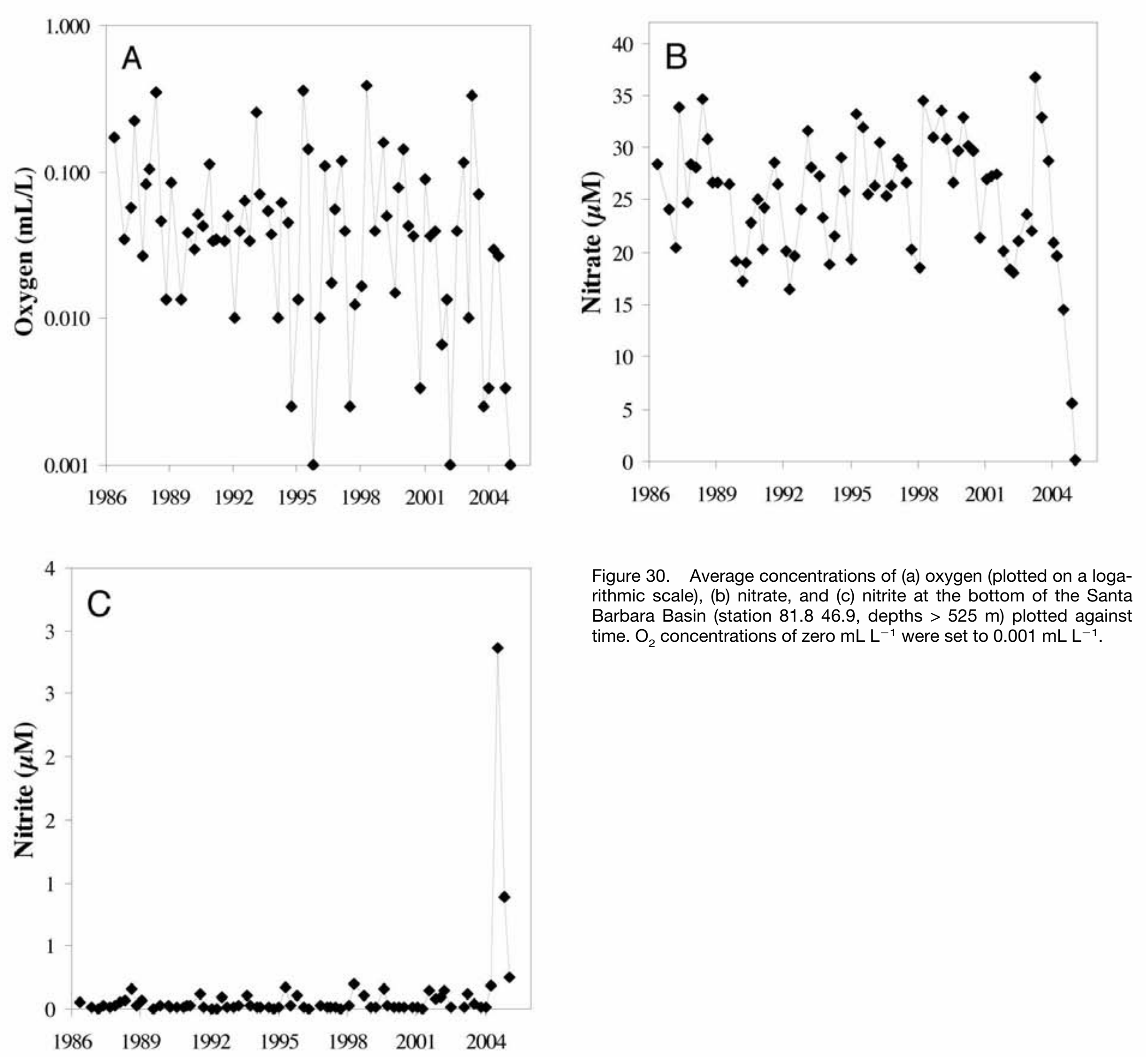

Figure 30. Average concentrations of (a) oxygen (plotted on a logarithmic scale), (b) nitrate, and (c) nitrite at the bottom of the Santa Barbara Basin (station 81.8 46.9, depths > 525 m) plotted against time. O_2 concentrations of zero mL L^{-1} were set to 0.001 mL L^{-1}.

mer were unusually high (fig. 31). In the offshore areas, the depth of the chlorophyll-*a* maximum had returned to a depth of ~100 m after two years at ~ 80 m (fig. 32a). The area of the CC is still characterized by slightly higher concentrations (fig. 32b) compared to the historical averages.

Macrozooplankton

Oregon: Inter-annual patterns of copepod biomass at the NH05 sampling station off Oregon (44°40'N; water depth 60 m) are shown in fig. 33. These seasonally integrated measures (May–Sept. average) of total copepod biomass indicate that 2004 was comparable to the preceding three years. The 2001–04 time period appeared to remain at a relatively stable state compared to either the lower levels observed during 1996–99 or the highly productive upwelling season of 2000. However, temporal resolution provided by bi-weekly sampling and species-specific data products provide evidence that suggests significant variability over the past four years.

Compared to observations during previous years, 2004 had substantial intra-annual variability in total copepod biomass, with some notable departures from the climatological mean (fig. 34). Rather than observing a late summer peak in copepod biomass, our sampling showed three events with high biomass values; the highest in May, and then two of a lesser magnitude in early July and early August. By early September, biomass showed a significant decrease, at least one month earlier than the "normal" fall transition, similar to patterns observed during 2003 (Goericke et al. 2004).

Anomalies in species-specific abundances have proven useful for relating the prevalence of copepod taxa with contrasting biogeographical affinities to inter-annual variability in ocean conditions (Mackas et al. 2001; Peterson

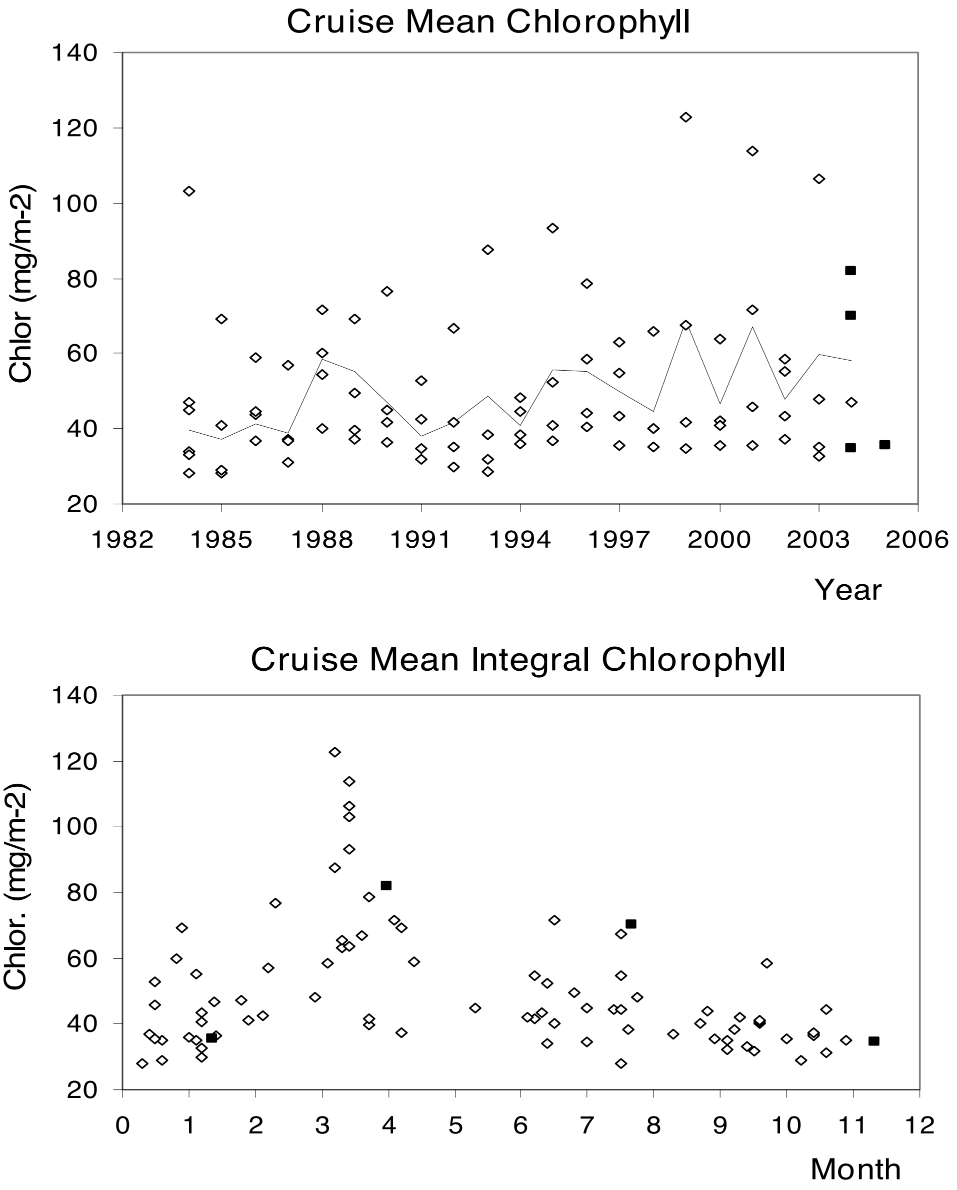

Figure 31. CalCOFI region chlorophyll-*a* standing stocks (mg per m^2). (a) plotted against time and (b) against the month (note that the 31st of January has a value of 1).

and Schwing 2003; Mackas et al. 2004). Prior to 1997, and particularly during the 1997–98 El Niño, copepod biomass was low and species with southern and off-shore affinities showed anomalously high abundances in coastal waters (Mackas et al. 2004). This group includes *Mesocalanus tenuicornis*, *Paracalanus parvus*, *Ctenocalanus vanus*, *Clausocalanus pergens*, *Clausocalnanus arcuicornis*, and *Clausocalanus parapergens*. This suggests that at least during the three-year period 1996–98, reduced coastal upwelling and low productivity characterized shelf waters of the northern CCS. However, following the onset of cool, La Niña-like conditions in 2000, copepod biomass doubled, and positive anomalies in the abundance of northern (cold water) copepod species were observed off Newport (and off Vancouver Island; Mackas et al. 2001). The abundant members of this group include species that dominate the waters of the Bering Sea shelf, coastal Gulf of Alaska, British Columbia coastal waters, and the Washington-Oregon coastal upwelling zone—*Pseudocalanus mimus*, *Acartia longiremis*, and *Calanus marshallae*. These indicators of "cold-water" conditions were common during the May–September upwelling season of 2000, 2001, and early portions of 2002 (Mackas et al. 2004). During 2003 and 2004, however, the biomasses of both warm water and cold water taxa were moderately high.

Hooff and Peterson[2] (submitted) have used biodiversity measures to characterize inter-annual variability in

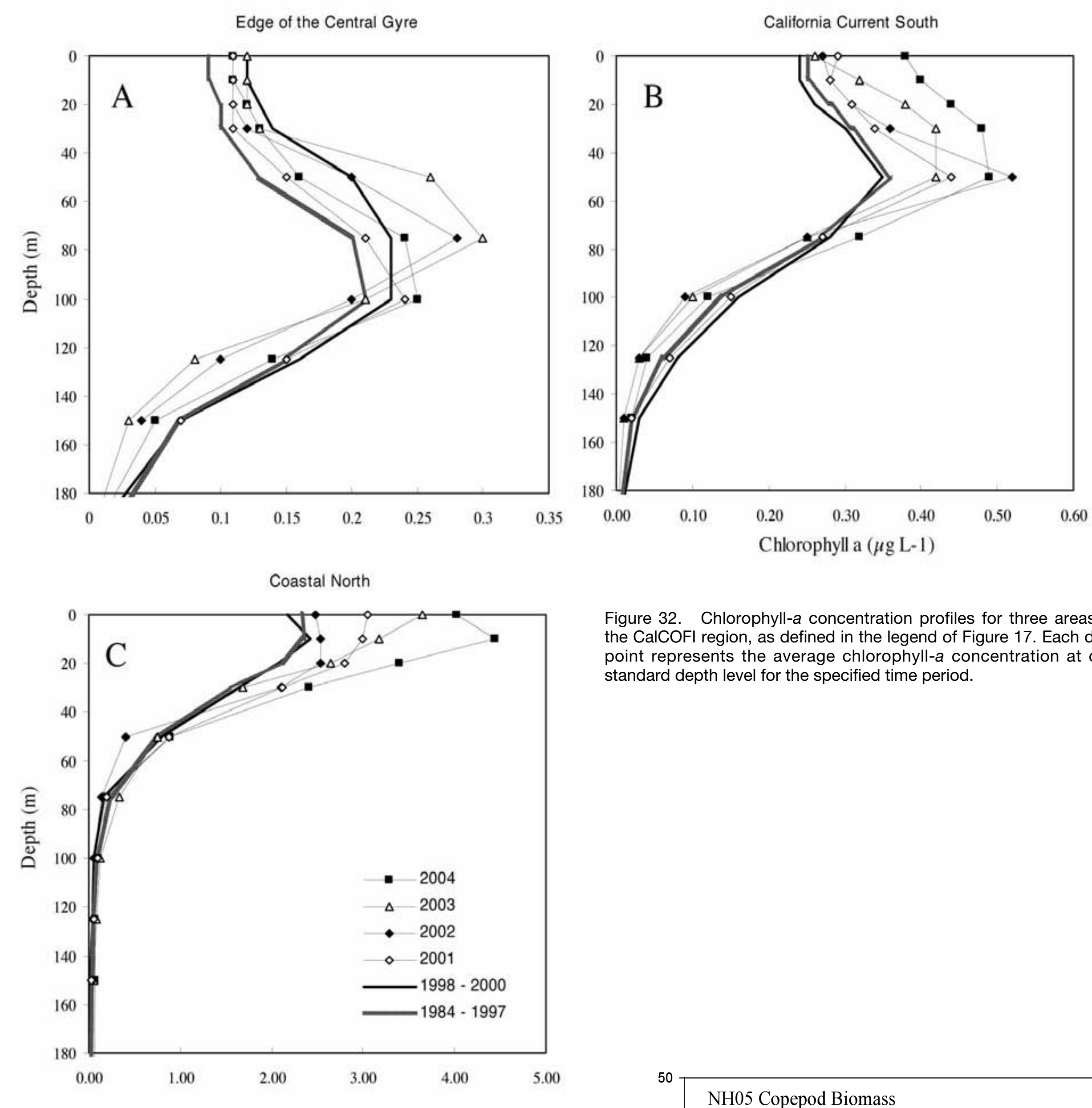

Figure 32. Chlorophyll-*a* concentration profiles for three areas of the CalCOFI region, as defined in the legend of Figure 17. Each data point represents the average chlorophyll-*a* concentration at one standard depth level for the specified time period.

copepod community composition and its relationship to recent changes in ocean conditions. Figure 35 compares seasonally detrended monthly anomalies of species richness with basinwide climatological indices (i.e. MEI and PDO). In general, copepod biodiversity increases during El Niño events, largely due to an increase of warm-water taxa of southern and/or offshore origins (Keister and Peterson 2003). A dramatic shift from anomalously high to anomalously low biodiversity levels is apparent in late 1998, following the strong El Niño event. Low biodiversity persisted for approximately two years after this shift. However, since 2000, levels have gradually increased. As indicated by the strong correspondence with the MEI and PDO, these recent changes appear to be related to regional or basinwide processes influencing

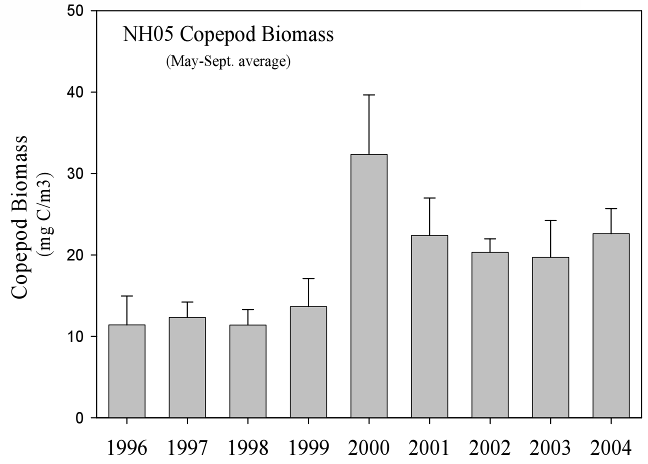

Figure 33. Inter-annual patterns of total copepod biomass (May–Sept. average ± standard error) at station NH05 of the Newport Hydrographic line (45°N, 60 m depth) for 1996 to 2004.

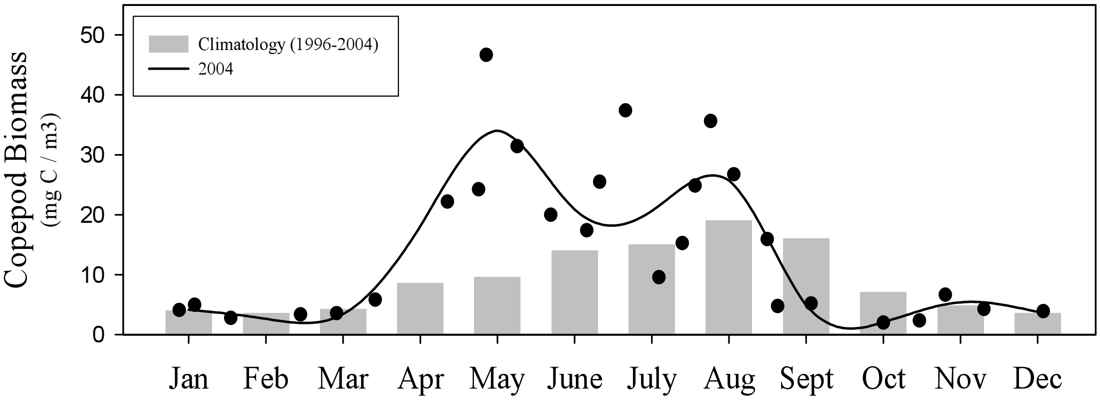

Figure 34. Total copepod biomass at station NH05 based on monthly averaged (line) and individual samples (scatter) compared to the 9-year monthly climatology (bars).

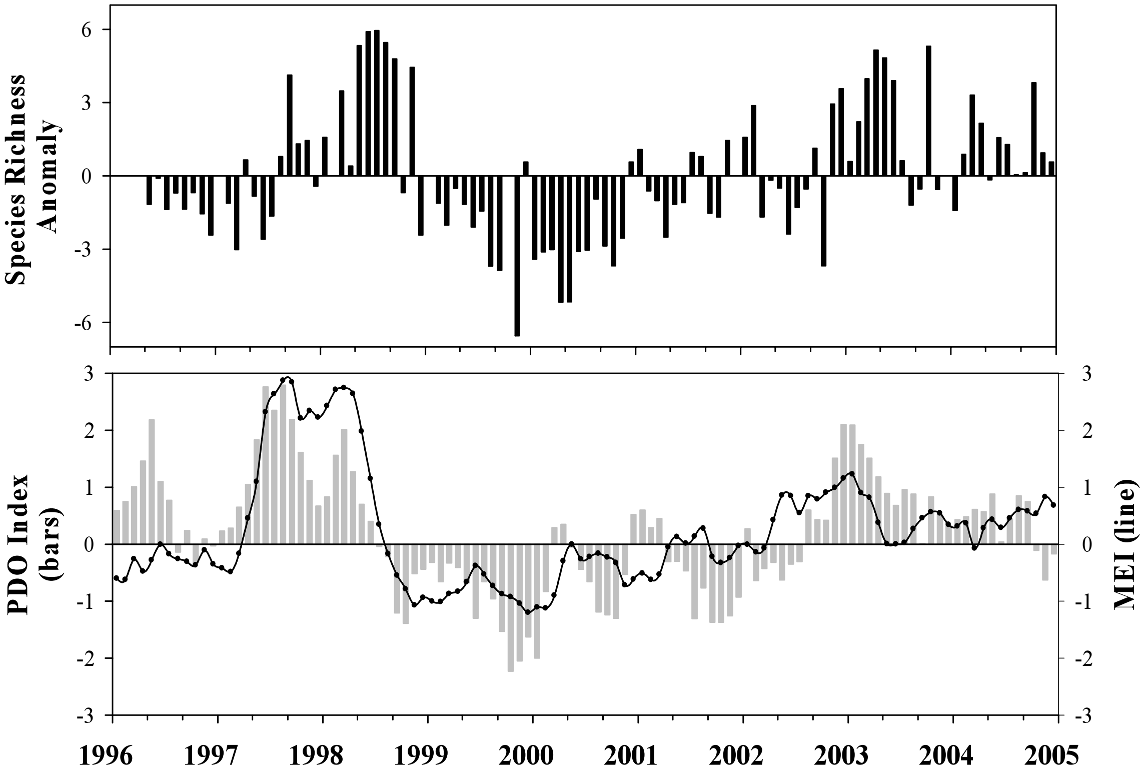

Figure 35. Seasonally de-trended monthly anomalies of copepod species richness at station NH05 off the Oregon coast (a), and monthly values of the MEI (line) and PDO (bar). For any given month, a negative value means fewer species than "normal" for that month; positive values indicate more species than normal. The presence of fewer species than normal is usually associated with cold waters; more species with warmer waters.

transport dynamics off the Oregon Coast. Biodiversity during the years 2003 and 2004 (and through the summer 2005) continues to be high and tracks recent changes in the PDO and MEI from negative to positive values. This suggests that the northern CCS has been under the influence of ocean conditions that are similar to an El Niño event, yet there has been no equatorial El Niño forcing. Another interesting aspect of the summers of 2003 and 2004 is the high abundances of two subtropical neritic copepods, *A. tonsa* and *C. anglicus*. Other details related to relationships between biodiversity, PDO and MEI are presented in Hooff and Peterson[2].

CalCOFI: Macrozooplankton displacement volumes during the observation period (86 ml/1000 m^3) were close to the climatological mean (113 ml/1000 m^3, 1984 to 2005 base period) and the mean for the 2000 to 2003 time period (fig. 36). Clearly, zooplankton bio-

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[2] Hooff, R.C. and W.T. Peterson. Submitted. Increased copepod biodiversity as an indicator of recent changes in climate and ocean conditions in the northern California Current ecosystem. Limnol. Oceanogr.

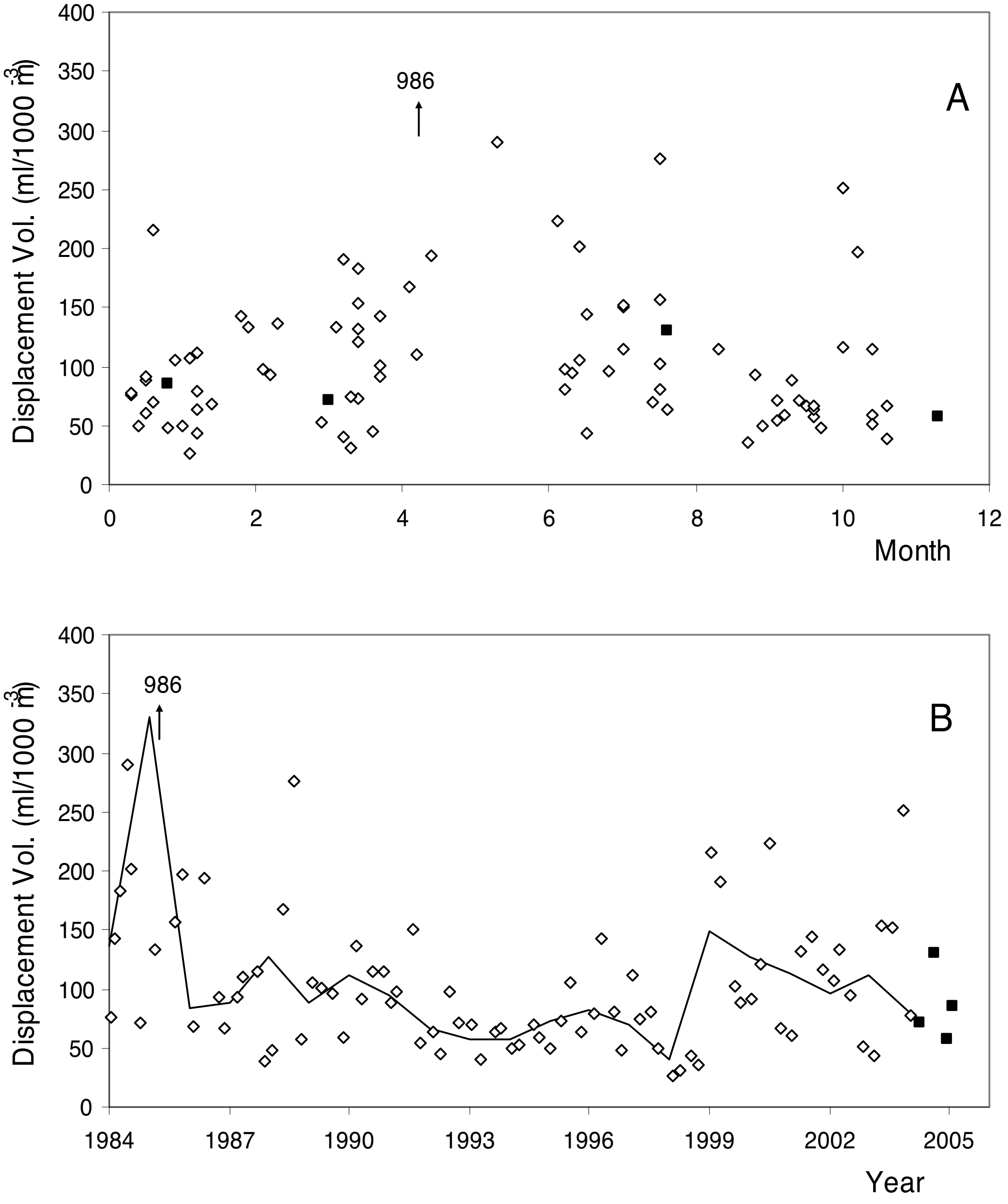

Figure 36. CalCOFI cruise mean macrozooplankton displacement volumes plotted against the month of the year (a) and the year (b). Data and symbol codes are the same as those in Figure 16.

mass has recovered from the dramatic decline of the 1990s. So far, no clear trends in zooplankton biomass since 2000 have emerged, making it difficult to relate changes in zooplankton biomass to climate indicators.

Fish Spawning

CalCOFI: In the spring of 2003, sardine, anchovy, and jack mackerel eggs were quite abundant compared to other recent spring values (fig. 37). Sardine eggs were most abundant between Santa Barbara and Monterey Bay, although they were also found along the southern and northernmost lines. Anchovy eggs, much less abundant than sardine eggs, were confined to the Southern California Bight. Jack mackerel eggs were offshore of the sardine eggs, with relatively little overlap, similar to previous years. The spatial distribution of sardine eggs in the spring of 2004 differed from previous years; very few eggs were found near and south of Point Conception. Most were found between Avila Beach and San Francisco. As the survey stopped at San Francisco, it was unclear whether the distribution of sardine eggs continued north of CalCOFI line 60. Again, in spring, 2004, anchovy eggs were found in the Southern California Bight, and jack mackerel eggs were found more offshore than anchovy eggs. Both anchovy eggs and jack mackerel eggs dominated the area south of Avila Beach. Overall, sar-

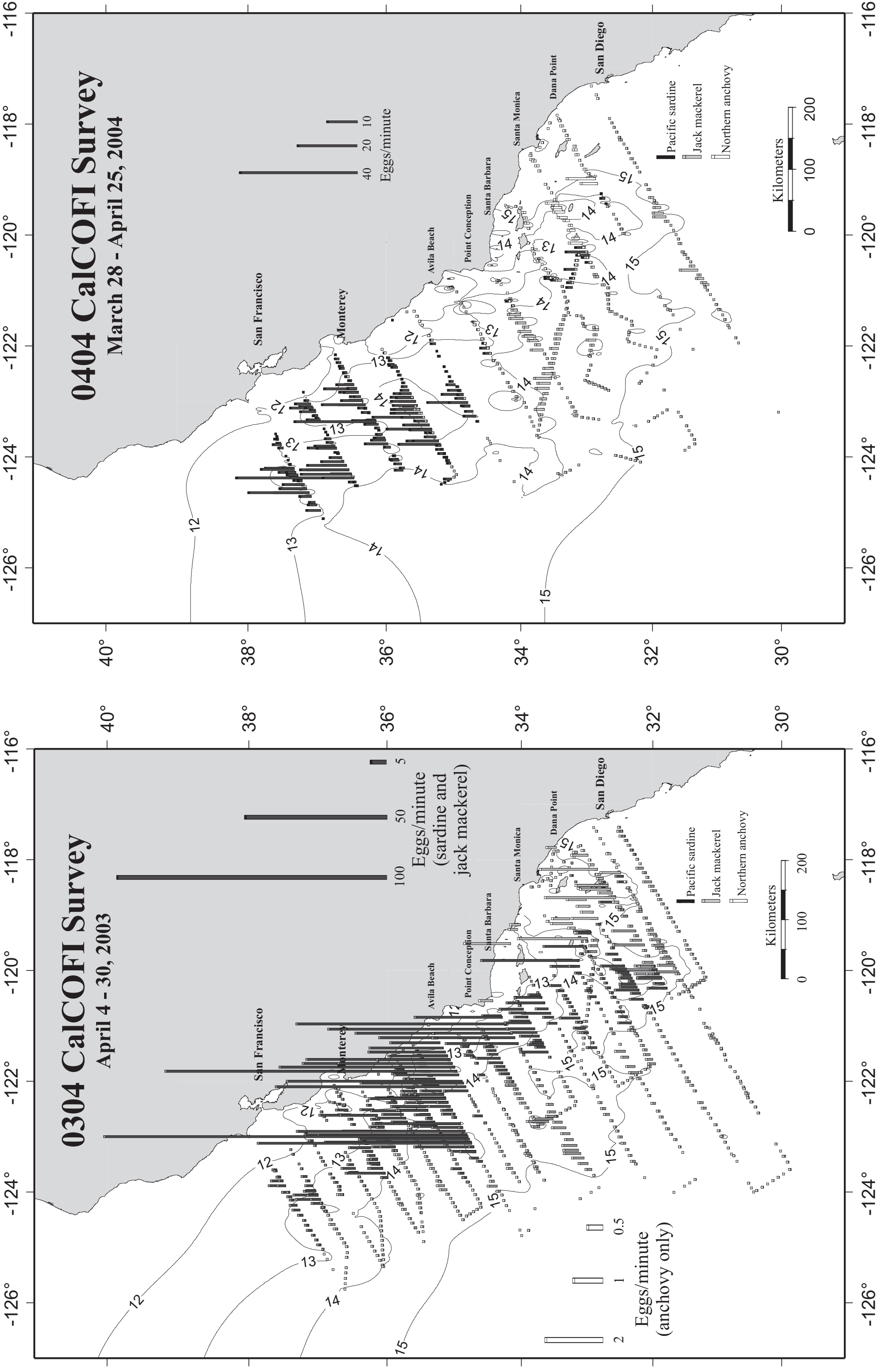

Figure 37. Rate of occurrence of eggs of Pacific sardine (*Sardinops sagax*), northern anchovy (*Engraulis mordax*), and jack mackerel (*Trachurus symmetricus*) sampled with the continuous underway fish egg sampler (CUFES) and sea surface temperatures in March–April 2003 and April 2004. One egg per minute corresponds to approximately four eggs per cubic meter

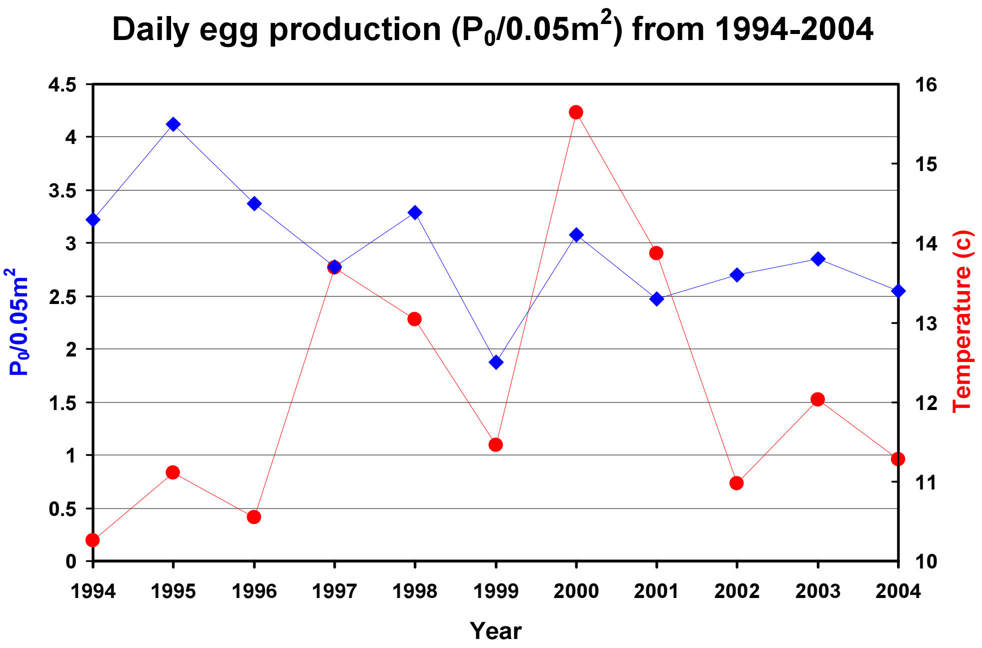

Figure 38. Daily egg production per 0.05 m^{-2} of Pacific sardine (circle) and average sea surface temperature (°C) (diamond) during March–April CalCOFI cruises from 1994–2004.

dine eggs were far more abundant than anchovy or jack mackerel eggs. Peak abundances observed in 2004 were similar to 2002 and less than 2003. During both 2002 and 2003, sardine eggs were found in the 12–14°C SST zone. In contrast, in 2004 few sardine eggs were found in the 12–14°C zone. Possible explanations for these observations are either a low spawning population or low spawning rates. Without adult samples taken in the low-density area, it is difficult to ascertain the causes of low sardine egg concentrations south of Point Conception in 2004. (For more information, see http://swfsc.nmfs.noaa.gov/FRD/CalCOFI/currentcruise/sardmaps.htm).

The spawning biomass of Pacific sardine is a fishery-independent population index, and it is useful to see how spawning was related to SST in the past years based on CalCOFI surveys. The spawning biomass of Pacific sardine is positively related to the daily egg production in particular if the number of oocytes per biomass weight remains constant (Lo et al. this volume). The relationship between the daily egg production per 0.05 m^2 and the average SST (°C) during 1994–2004 indicated that in most years the relative peaks in egg production coincided with elevated SST; exceptions are the years 1997 and 2002 (fig. 38). The observed relationship is consistent with the assertion that high temperature is favorable for the Pacific sardine (Jacobs and MacCall 1995).

Avifauna

This report focuses on spring and summer observations of marine bird populations made on CalCOFI cruises and on studies of diet and reproductive performance carried out on the Farallon Islands, which are located on the edge of the continental shelf west of San Francisco. We focus on the spring–summer period since this is a sensitive phase in the seabird seasonal cycle of breeding effort and migration (Schwing et al. 2000; Sydeman et al. 2001). Figures 39 and 40 extend past observations through 2004.

The most unusual single avifaunal event of this past year was the extremely poor breeding success of Cassin's auklet (*Ptychoramphus aleuticus*) on the Farallon Islands. There is also evidence that this species did not attempt breeding on the Channel Islands in 2004[3]. One inference is that zooplankton prey (the euphausiids *Euphausia pacifica* and *Thysanoessa spinifera*) may have been unavailable in 2004. Such reproductive failure was unprecedented since monitoring of these populations began in the mid-1980s and will be followed closely.

Our long-term objective is to characterize the response of the avifauna to the 1998 transition from a warm- to a cold-water regime (Schwing et al. 2002; Peterson and Schwing 2003; Venrick et al. 2003). To do so, we compare seabird abundance, diet, and productivity during the years 2000 to 2003 with those of 1990 to 1997. The avifauna of the CCS is influenced by northward incursions of subtropical species during warm-water periods and by the southward movement of subarctic species during cold-water periods (Hayward et al. 1999; Hyrenbach and Veit 2003; Venrick et al. 2003). To illustrate interannual and longer-term fluctuations in

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[3] P. Martin, Channel Island National Park, pers. comm.

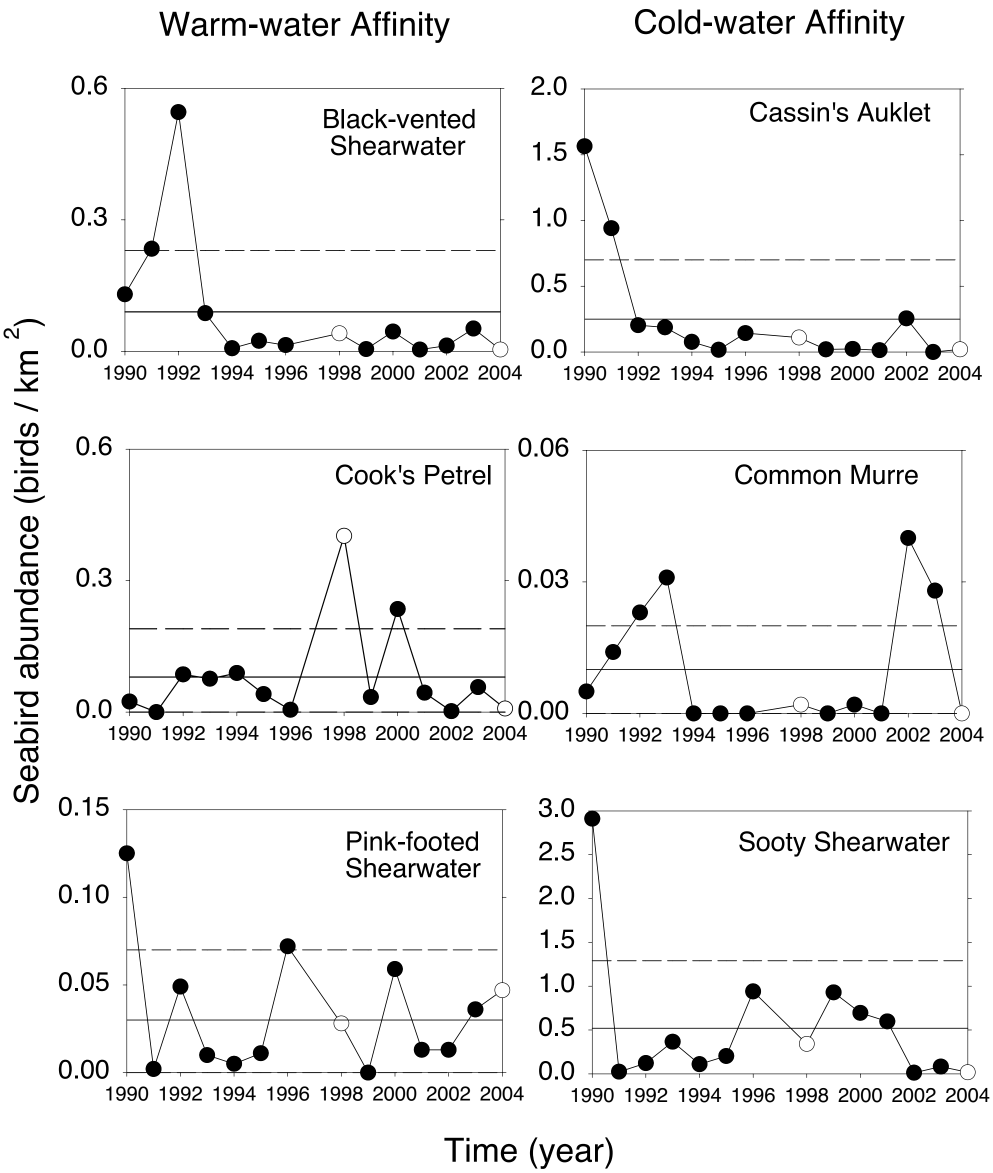

Figure 39. Anomalies of at-sea abundance of six seabird species with different water temperature affinities. The long-term averages (1990–2004) are depicted by the solid horizontal lines; the hatched lines illustrate the variability (mean ± 2 S.D.). Filled circles highlight abundance values during the base periods before (1990–97) and after (1999–2003) the regime shift during the winter of 1999. Note: there were no at-sea surveys in the spring of 1997.

the composition of marine bird communities, we focus on six indicator species with different water mass preferences and biogeographic affinities. We considered three subtropical species, which breed south of the CalCOFI study area and have an affinity for warm-water conditions. The pink-footed shearwater (*Puffinus creatopus*) occurs off southern California waters between spring and fall and becomes most numerous after El Niño events (Hyrenbach and Veit 2003). The Cook's petrel (*Pterodroma cookii*) also occurs off southern California during spring–fall and reaches the highest densities during periods of warm-water anomalies (Hayward et al. 1999). Large numbers of black-vented shearwaters (*Puffinus opisthomelas*) enter the CalCOFI study area in fall, especially during El Niño events, and remain in the area over winter and spring (Hayward et al. 1999; Hyrenbach and Veit 2003). We also considered three subarctic species with an affinity for cold-water conditions (Hyrenbach and Veit 2003). The sooty shearwater (*P. griseus*), a spring–summer–fall visitor from the southern hemisphere, and two locally breeding species: the planktivorous Cassin's auklet, and the piscivorous common murre (*Uria aalge*).

No significant temporal trends were detected for the pelagic densities of the indicator species. Only the subtropical black-vented shearwater showed a marginally significant decline of 84% ($p = 0.088$) between 1990–

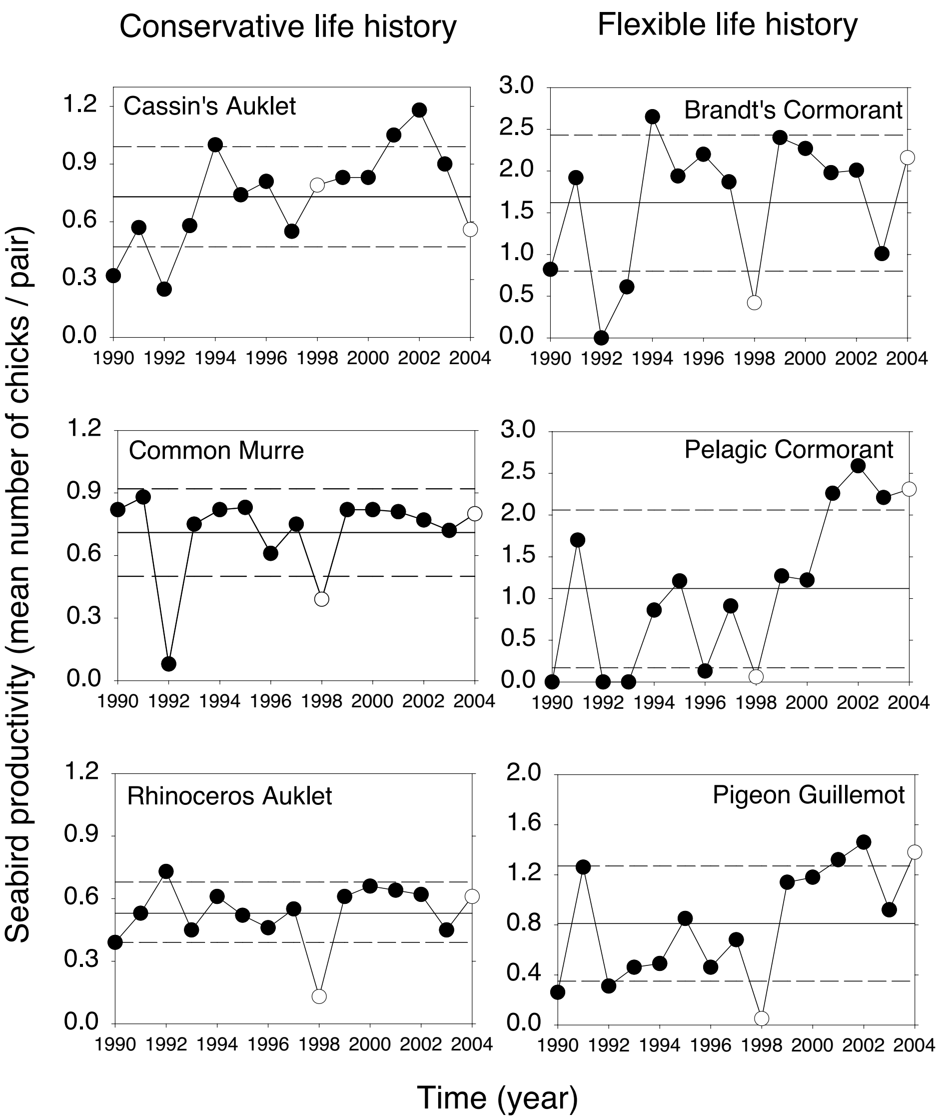

Figure 40. Anomalies of productivity for six seabird species breeding at SE Farallon Island (central California). The long-term averages (1990–2004) are depicted by the solid horizontal lines; the hatched lines illustrate the variability (mean ± 2 S.D.). Filled circles highlight abundance values during the base periods before (1990–97) and after (1999–2003) the regime shift during the winter of 1999.

TABLE 1

Comparison of the abundance of six indicator species within the CalCOFI survey grid (southern California), in conjunction with the 1998–99 regime shift. The proportional change in seabird productivity was quantified as PC = 100% * [(after) – (before)/(before)]. Positive and negative PC values are indicative of increasing and decreasing productivity respectively. For each species, the biogeographic affinity (ST: subtropical, SA: sub-arctic) and breeding status in the California Current (B: breeding, NB: non-breeding) are shown.

		Abundance (birds/km²)				
		(mean ± SD)				
Seabird Species	Life History	(1990–97)	(1999–2003)	Proportional Change (%)	Mann-Whitney U	*p* Value
Black-vented Shearwater	NB–ST	0.15 ± 0.19	0.02 ± 0.02	–83.95	28	0.088
Pink-footed Shearwater	NB–ST	0.04 ± 0.05	0.02 ± 0.02	–37.61	18	0.935
Cook's Petrel	NB–ST	0.05 ± 0.04	0.07 ± 0.09	+62.88	16	0.808
Cassin's Auklet	B–SA	0.45 ± 0.58	0.06 ± 0.11	–86.11	27	0.123
Common Murre	B–SA	0.01 ± 0.01	0.01 ± 0.02	+34.88	16	0.801
Sooty Shearwater	NB–SA	0.67 ± 1.04	0.46 ± 0.40	–30.63	19	0.808

TABLE 2

Comparison of the productivity of six seabird species breeding at the Farallon Islands (central California), in conjunction with the 1998–99 regime shift. The proportional change in seabird productivity was quantified as PC = 100% * [(after) – (before)/(before)]. Positive and negative PC values are indicative of increasing and decreasing productivity respectively. Bold font denote statistical significance at the alpha = 0.05 level. For each species, the reproductive strategy (F: flexible, C: conservative) and the diet (P: piscivore, Z: zooplanktivore) are shown.

		Productivity (chicks fledged/pair)				
		(mean ± SD)				
Seabird Species	Life History	(1990–97)	(1999–2003)	Proportional Change (%)	Mann-Whitney U	*p* Value
Brandt's Cormorant	F–P	1.50 ± 0.91	1.93 ± 0.55	+28.83	17	0.463
Pelagic Cormorant	F–P	0.60 ± 0.66	1.91 ± 0.62	+217.67	2	**0.006**
Pigeon Guillemot	F–P	0.60 ± 0.33	1.20 ± 0.20	+101.93	3	**0.009**
Cassin's Auklet	C–Z	0.60 ± 0.25	0.96 ± 0.15	+59.00	8.5	0.062
Common Murre	C–P	0.69 ± 0.26	0.79 ± 0.04	+13.79	25.5	0.686
Rhinoceros Auklet	C–P	0.53 ± 0.11	0.60 ± 0.08	+12.45	12.5	0.180

97 and 1999–2003 (tab. 1). This warm-water indicator occurred in large numbers off southern California during 1990–93, during a protracted warm-water period (Chavez 1996; Trenberth and Hoar 1997), and declined thereafter (tab. 1). The two other warm-water indicators (Cook's petrel and pink-footed shearwater) varied substantially from year to year and did not show a consistent response to the 1998–99 regime shift (tab. 1). Cook's petrel occurred at "average" levels during the 1992–95 warm-water period and was most numerous during the 1997–98 El Niño (fig. 39). The abundance of the pink-footed shearwater has increased significantly in the CalCOFI study area over the long-term when all four seasons are considered (1987–98) (Hyrenbach and Veit 2003), but its spring-time abundance was highly variable and the decline after the 1998–99 regime shift was not statistically significant (tab. 1).

Nor did the at-sea densities of the three cold-water indicators show a significant response to the 1998–99 regime shift (tab. 1). Sooty shearwater numbers declined from a maximum in 1990, remained low during the protracted 1992–95 warm-water period, and rebounded slightly during 1996–97 and 1999–2001 (fig. 39). When all seasons are considered, however, this species has declined significantly over the long-term (1987–98) (Hyrenbach and Veit 2003). Likewise, the Cassin's auklet declined by an order of magnitude early on and remained at low densities after 1992, rebounding only slightly in 2002 after the onset of cold-water conditions. The common murre showed a different response, with anomalously high densities at the beginning (1992–93) and the end (2002–03) of the time series. The murre was present in very low average densities (<0.01 birds km^{-2}) during spring-time cruises, both before and after the 1998–99 regime shift (tab 1). However, population-level responses of auklets and murres to changes in environmental conditions and reproductive success occur with a three- to five-year lag, due to the age of reproductive maturity in these species (Pyle 2001)[4], so it may still be premature to expect their pelagic abundances to clearly reflect a regime shift.

Because seabird reproductive success depends directly upon oceanographic conditions and prey availability during breeding season, we expect an immediate response of seabird productivity to recent oceanographic changes (Sydeman et al. 2001). The productivity of marine bird populations breeding at the Farallon Island (fig. 40) increased during 1999–2002 (Venrick et al. 2003). After declines in most species during the 2003 El Niño (Goericke et al. 2004), most species—except the planktivorous Cassin's auklet—returned to high productivity levels in 2004. Over the long-term, we documented statistically significant changes in productivity for two of the six species monitored (tab. 2). These two are piscivores; one is neritic and one benthic (pelagic cormorant and pigeon guillemot). They more than doubled their productivity after the 1998–99 regime shift (tab. 2). The Brandt's cormorant, whose productivity can be decoupled from that of the other piscivores (Sydeman et al. 2001), did not experience a long-term increase in productivity. The increased productivity of the three locally-breeding species with more conservative life histories (one-egg clutches) was not significant (tab. 2).

The enhanced productivity of locally-breeding piscivores (pelagic cormorant and the pigeon guillemot) has taken place during a return of juvenile rockfish (*Sebastes* spp.) as a major prey constituent for seabirds (Miller and Sydeman 2004). After a period of very low average (0.15 + 0.12% S.D.) rockfish in the murre chick diet (1990–2000), this item increased substantially to over half of the diet (0.58 + 0.14% S.D.) during the last few years (2001–03). These values are comparable to those observed between 1973 and 1989 in the CCS (0.63 + 0.2 % S.D.) (fig. 41).

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[4] Point Reyes Bird Observatory, unpub. data.

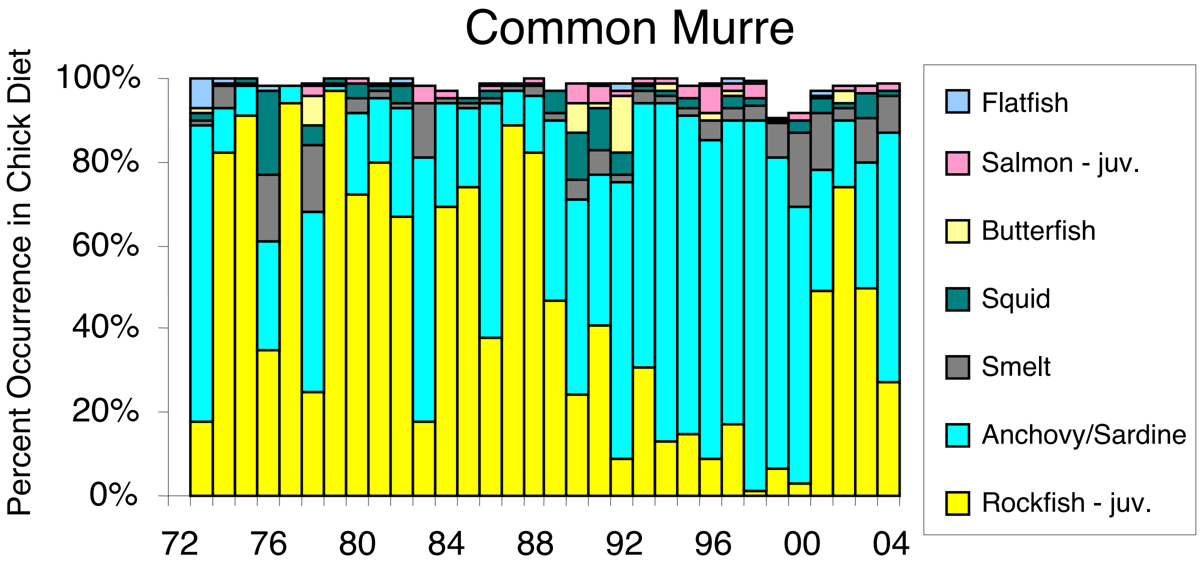

Figure 41. Inter-annual diet composition of common murre chicks at SE Farallon Island (central California, 1973–2004), based on the number of prey items of each species consumed. Other dietary items include Pacific butterfish (*Peprilus simillimus*), juvenile salmon (*Oncorhynchus* spp.), flatfishes (*Bothidae* and *Pleuronectidae*) juvenile lingcod (*Ophiodon elongatus*), señorita (*Oxyjulis californica*), and other fish species comprising less than 5% of the diet in any year.

DISCUSSION

The focus of this discussion is the state of the California Current System (CCS) in relation to leading indicators of climate and the effect of the subarctic water on the system. The weak tropical El Niño of 2004 did not appear to have a noticeable effect on the CCS. Hydrographic effects failed to propagate to the coast of South America. Unrecognized effects via atmospheric teleconnections can not be ruled out; some of the recent warm SST anomalies may have been associated with atmospheric anomalies related to the tropics. However, variations of physical or biological indicators—mixed layer depths, temperature anomalies, biomass of zooplankton or avifauna—over the last year do not suggest that these were forced by an ENSO event (see also Goericke et al. 2004).

The Evolution and Effects of the Subarctic Influence

One of the more unusual phenomena over the past few years was the large-scale intrusion of cold and fresh (minty) subarctic water into the CCS. This was first noticed off British Columbia and Oregon (Freeland et al. 2003), but quickly spread further south (Venrick et al. 2003; Goericke et al. 2004; Durazo et al. 2005). Off Oregon it appeared to wane over the last year—salinity anomalies in the upper thermocline were returning to normal. In contrast, in the CalCOFI and IMECOCAL region 2004 salinity anomalies continued strong (figs. 16, 17). The intrusion of the minty water into the CalCOFI region and the associated uplift of the seasonal thermocline in the offshore areas (figs. 17, 27) had a significant effect on the location of the chlorophyll maximum in the offshore areas (fig. 32). It remains to be seen if the strong silicate anomaly off southern California (fig. 28c) is related to the intrusion of the subarctic water. Historical hydrographic data from CalCOFI suggest that alternating periods of cool-fresh and warm-salty waters have affected the CCS in the past, although the recent anomalies are the strongest on record. Broad changes in the gyre-scale circulation in the northeast Pacific, possibly related to regime-scale variability, could lead to increased transport of subarctic waters into—and enhanced equatorward transport within—the CC.

The Evolution of the Post-1998 Cold Phase

The change in the sign of the PDO after the El Niño of 1998 was dramatic. Even though current climatologies no longer support the characterization of the state of the North Pacific as a negative PDO phase, patterns of SST in the CCS support the contention that the system is still in a slightly cool phase (figs. 12, 15). Biological properties also suggest that at least some regions underwent significant changes in 1998 and have remained in this new state. These include copepod biomass and community species richness off Oregon (fig. 33, 35), chlorophyll-*a* in Monterey Bay (fig. 12), and zooplankton biomass in the CalCOFI region (fig. 36). Other properties, however, appear unaffected by changes in ocean climate indices. For example, annually-averaged chlorophyll-*a* in the CalCOFI region appears to have increased since the 1980s but defies more detailed analysis due to the large variability in the data. Similarly, daily egg production of the Pacific sardine (fig. 38) did not appear to respond to the 1998 regime shift.

Avifaunal evidence for a long-term switch to cold-water conditions in 1999 is mixed. The colony-based data revealed an increase of piscivore productivity in 2004 after a decline in 2003, continuing a trend observed during the previous four cold-years (1999–2002) (Schwing et al. 2002). Even though this demographic response is statistically significant for only two of the six species monitored at the Farallon Islands, this result suggests that breeding seabird populations continue to benefit from the transition into a cold-water regime of enhanced upwelling and prey availability. The Farallon Island productivity data suggest the possibility of a subsequent increase in the abundance of avifauna at-sea, but this did not occur. The pelagic abundances of both cold-water and warm-water indicators showed changes, but there were no significant trends indicative of a regime shift to cold water conditions after 1998–99 (tab. 1). Indeed, changes were inconsistent with the environmental affinities, with one warm-water species increasing in recent abundance and one cold-water species decreasing.

In summary, it appears that the CCS is currently in a cold phase, but many biological parameters and some physical parameters did not respond consistently to this change in phase that occurred in 1998. This suggests that the forcing of the system associated with this change in phase was weak and was in many instances overpowered by other forcing occurring on interannual scales, i.e. ENSO cycles, variations in the transport of the CC, etc. As a consequence, we will not speculate on the evolution of the system during the coming year.

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Part II

SYMPOSIUM OF THE CALCOFI CONFERENCE, 2004

La Jolla, California
16 November 2004

PACIFIC SARDINE: PAST, PRESENT, AND FUTURE

Over 55 years ago, the rapid decline of the Pacific sardine (*Sardinops sagax*) resource sparked the formation of the California Cooperative Sardine Research Program, an inter-agency research program now called CalCOFI. CalCOFI has evolved over the years to address a much broader range of scientific questions about the California Current ecosystem but, at the same time, has been reduced in geographic scope and sampling frequency relative to the historic program. Fortunately, CalCOFI has survived to help document recovery of the Pacific sardine resource. CalCOFI continues to play a vital role in our population assessments and contributes to understanding connectivity between the California Current ecosystem and sardine population dynamics and productivity.

Unfortunately, many of the basic scientific questions posed by pioneers like Frances Clark, Jack Marr, and Garth Murphy remain unanswered today. While the latest sardine recovery began with an improved understanding of the past, current relevance of the historical perspective must be tempered with the realization that the recovery has occurred under a different set of conditions, favorable to the population's return. Thus, our preconceived notions regarding stock structure, movement, and productivity should be viewed with some skepticism and investigated with even more vigor.

The good news is that a new generation of scientific tools and data is available to assess the sardine's present status and forecast the future. From the onset of the sardine's recovery, new research and monitoring programs were initiated from México to Canada. Efforts are underway to coordinate and implement synoptic resource surveys, coast-wide, on a regular basis. The sardine population can be monitored in "real-time" using Continuous Underway Fish Egg Samplers (CUFES) coupled with advanced hydroacoustic and aerial (LIDAR) technologies currently under development. Population assessments, the basis for annual management in the U.S. and Canada, are accomplished using sophisticated statistical catch-at-age models and advanced computing power, light years beyond tools available to Garth Murphy in the early 1960s. The harvest policy adopted in the U.S. fishery management plan includes a simple, yet innovative, environmentally-based component linking fishery exploitation rate to prevailing oceanic conditions.

International management agreements are still needed to ensure the future stability of this trans-boundary resource, which is now fully utilized through the combined harvest of México, the U.S., and Canada. In the meantime, international scientific collaboration has been nurtured through the Trinational Sardine Forum, which has met annually since the year 2000. The goal of the proceeding joint CalCOFI-Trinational Sardine Forum Sardine Symposium was to highlight results from the latest sardine research and provide a venue for open discussion about the present and future status of the sardine resource.

The articles presented here were refereed by at least two external reviewers and edited by Sarah Shoffler. We wish to thank all the symposium participants for their contributions.

Kevin Hill
Tim Baumgartner

A HISTORY OF PROPOSALS FOR SUBPOPULATION STRUCTURE IN THE PACIFIC SARDINE (*SARDINOPS SAGAX*) POPULATION OFF WESTERN NORTH AMERICA

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ABSTRACT

Recent work has examined the structure of stocks, races, or subpopulations in the recovering Pacific sardine (*Sardinops sagax*) biomass of the northeast Pacific Ocean. Individual fish characteristics do not clearly indicate the geographic origin of birth, but collections of sardines from different areas show some heterogeneity in growth rate, time of birth and recruitment, blood type, and number of vertebrae. Even when heterogeneity is in question, precautionary management principles, which reduce the risk of overfishing, should support management of stocks of fish in different areas as independent stocks.

The sardines of the northeast Pacific have been estimated to have up to three subpopulations based on tagging, size-at-age, isolated spawning centers, blood groups, vertebral column counts, estimated natural mortality rate, or bimodal seasons of recruitment. Spawning centers are thought to occur off the Gulf of California (GOCAL), Baja California Sur inshore (BSI) and Central California offshore (CCO). Cursory genetic examinations of sardines from these areas neither support nor refute these divisions. Genetic analysis of *S. sagax* from four far-flung sardine habitat sectors of the Pacific basin can be described as "shallow," meaning the separation of all the species in the Pacific is relatively recent. However, on the time scale of fisheries management, decades, the separation of the two stocks on the Pacific coast, BSI and CCO, appears chronic in that the collapse of the northern stock did not stimulate an apparent replacement from the southern stock in decades. Therefore, it would be prudent to institute separate management measures that define the boundary between GOCAL and BSI and the boundary between BSI and CCO regardless of the genetic or habitat basis for stock separation. Three data-rich bases for describing the two stocks' modern isolation should be used to design careful studies of representative samples of sardines at the boundaries between the stocks for devising the most practical method for allocating catches among the neighboring stocks.

This paper reviews existing data to see which might be applied to a precautionary approach to managing the revived Pacific sardine fisheries. It also examines what advances in our knowledge of these stocks and the methods used to assess them may be required to ensure an adequate spawning biomass and yield of the sardine fisheries for the northeast Pacific stock(s).

INTRODUCTION

Theories of precautionary management, postulated to reduce the risk of overfishing to a minimum, depend on adequate knowledge of the location and movements of self-sustaining populations and the geographic distribution of landings. At least one stock of Pacific sardines (*Sardinops sagax*) in the northeast Pacific has increased in biomass from low levels in the 1960s and 1970s to a currently managed fishery spanning the Pacific coast from México to Canada (Conser et al. 2004).

The primary purpose of this paper is to review existing data to see which might be applied to a precautionary approach to managing the revived Pacific sardine (*Sardinops sagax*) fisheries. Further, some advancement in our knowledge of these stocks and the methods used to assess them may be required to ensure an appropriate spawning biomass and yield of the sardine fisheries for the northeast Pacific stock(s).

INDICATIONS OF SUBPOPULATION STRUCTURE

Early efforts at describing and monitoring the sardine fishery used only size-frequency and catch location data (Clark 1931). A geographically massive tagging program set a standard for characterizing rapid and extended sardine migrations from northern México to British Columbia. Early attempts at aging the fish were not successful (Thompson 1926), and early meristics studies supported a single stock hypothesis (Hubbs 1925).

Clark (1935) regarded the West Coast stock of sardines as a single population that spawned in the south off California and whose larger fish migrated successively further north up to the Gulf of Alaska. This describes the geography of a single stock (fig. 1a)[1]. Tagging soon directly supported this model; tags originating from almost all tagging sites were recovered at northern California fishmeal plants. An exception was noted for sardines tagged and released off southern Baja California.

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[1] O. E. Sette (deceased). 1935. unpub. ms.

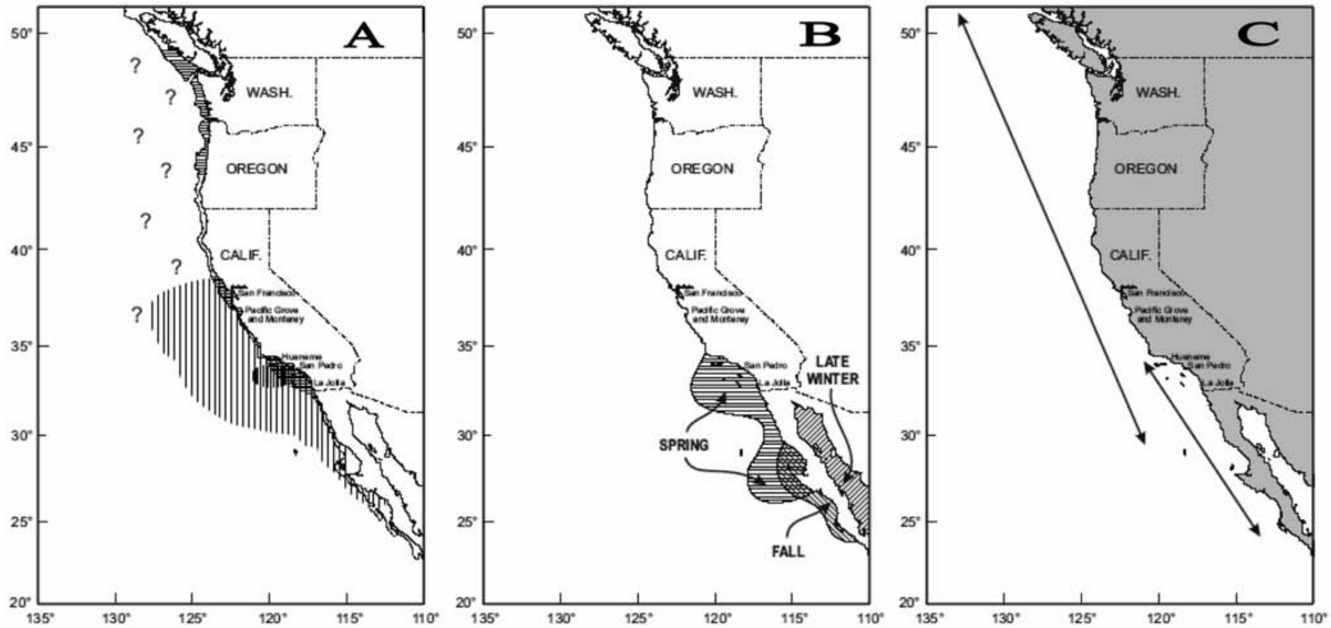

Figure 1. The coastal extent of the major Pacific sardine (*Sardinops sagax*) fisheries, spawning habitat, and migratory range. A) An unpublished diagram of the fisheries (horizontal lines) and spawning areas (vertical lines) showing unmeasured regions (?) for spawning based on knowledge in 1935[a]. B) A diagrammatic summary of sardine spawning centers and seasons based on the 1952–1956 CalCOFI surveys (Marr 1960). C) A diagram of the internal boundaries of the migratory range as postulated by Felin (1954), and updated by a geographic review of vertebral counts (Wisner 1960) and blood groups (Sprague and Vrooman 1962; Vrooman 1964) and range northern extent (McFarlane et al. 2002).

None were retrieved in the northerly fishmeal plants (Marr 1957). It was concluded that the fish landings from British Columbia to central and northern Baja California came from a common stock (Clark and Jannson 1945). Godsil's[2] unpublished paper, however, reported that sardines recruit to San Diego fisheries in April and August.

Once aging from scales and otoliths became available (Walford and Mosher 1943a), two radically different growth patterns were detected (Felin 1954): a stock of small sardines in the south and a stock of larger sardines in the north. At three years, the modal northern sardine length was 219 mm standard length, and the modal southern sardine length was 193 mm. The northern three-year-old sardine was about 50% heavier than the southern. Felin (1954) concluded as follows:

> The possibility of heterogeneity in stocks of *Sardinops caerulea* along the Pacific coast of the United States and Canada is examined through evidence from growth and vital statistics of the fished population(s). Growth characteristics of six year-classes sampled in Canada are compared with those from San Pedro. Significant difference in predicted size indicates lack of homogeneity in populations of adults as sampled by the fishery in Canada and in San Pedro. Evidence from qualitative and quantitative differences in individual scale and growth patterns indicates some independence in the fished stock of the Pacific Northwest and southern California. Bimodality in length composition of certain year classes is evidence that pilchard populations are not homogeneous. Large, long-ranging pilchard may arise from spawning stocks off California while more southern stocks, smaller in size and more short-lived, have limited migration. In view of indications of heterogeneity in growth types of fished stocks of pilchard, whether genotypic or phenotypic in origin, it appears desirable that their population dynamics be studied not only for the coast as a whole but also by geographic areas.

The most comprehensive review of population structure and dynamics was conducted by Marr (1960). Marr assembled and analyzed all of the data from the Pacific sardine fishery, tagging information, and fishery independent surveys of sardine eggs and larvae that were available at the time. Because there were negligible sardine data from the small Mexican fisheries before that time, it was impossible to include data on this southern stock beyond that collected from occasional catches in warm years at San Pedro. The early spawning data collected from off BSI were best described during the "cold" CalCOFI years up to 1956 (Marr 1960).

The early fishery for sardines supported several commercial products, many derived from European prod-

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[2] H. C. Godsil. 1932. Untitled manuscript. Available at: Southwest Fisheries Science Center Library, 8604 La Jolla Shores Drive, La Jolla, CA 92038.

[a] O. E. Sette (deceased). 1935. unpub. ms.

ucts: fish meal and oil, bait, fresh and canned fish. There were three sizes of sardine cans. The principal California fisheries provided fish mostly for the one-pound oval can (454 g), lesser quantities for the half-pound oval (227 g), and least of all for the "quarter"-pound square (114 g). The size structure of sardines along the coast determined in what ports each size can was filled. There were two dominant size groups in San Pedro that were canned in the one-pound oval: generally 10 fish per can except during February and March when larger sardines dominated the pack with five fish per one-pound oval (Higgins 1926). In retrospect, this may indicate that an area exists where the different size fish could support an overlap zone that includes San Pedro. "Quarters" were juvenile sardines canned in oil in San Diego in the quarter-pound square can. The sport bait and "quarter oil" cannery drew on two cohorts of juveniles: one appeared in the spring, called the "spring" quarters, and one in the fall, called the "local" quarters[3].

The seasonal and geographic distributions of spawning are the most important data available to describe the geographic separation of the stocks. The most extensive continuous spawning area is currently off Central California in April (Lynn 2003). Spawning also appears to narrowly extend north to the coastlines off Canada and Alaska and south to Cedros Island and Sebastián Vizcaíno Bay off the coastline of northern and central Baja California. The Gulf of California (GOCAL) is also a site of geographically extensive sardine spawning in late fall and winter (Aceves-Medina et al. 2004).

The most enigmatic of the putative stocks is the inshore spawning population centered near Magdalena Bay, Baja California Sur (BSI) which has a spawning peak in summer. In some years this spawning has extended in a narrow coastal band north to the coast of southern California. The southern limit toward Cape San Lucas is not well known (Ahlstrom 1959; Marr 1960; here fig. 1b). The Marr (1960) spawning diagram is probably the best representation of the spawning centers, but it is drawn from the early cold years of CalCOFI. The contemporary spawning center of the CCO (Central California offshore) sardine is about 500 km (300 nmi) north of the 1939–41 spawning center targeted by Sette and Ahlstrom (1948).

The possible genotypic foundation for geographic limits to the BSI and CCO subpopulations was developed with erythrocyte antigen methods ("blood type") by 1960 (Sprague and Vrooman 1962). Vrooman (1964) reviewed the outer coastal data and reported additional erythrocyte antigen results from GOCAL. The age structure of the outer coast stocks in the southern California fishery showed that the CCO sardines were from the 1956 and 1957 year-classes and that the BSI sardines were from the 1958 and 1959 year-classes. A seasonal migration of the two stocks may overlap spatially, but not at the time of spawning. A summary of the blood type data is found in Table 1 with the statistically assigned stock origins.

A summary of geographic data from the 1930s, which supports the idea of a single stock (Clark 1935)[4], is shown in Figure 1a. The location of the spawning centers of the early 1950s (Marr 1960) is reproduced in Figure 1b. The location of the former spring spawners coincides with the location of the CCO stocks currently monitored in April; the location of the former fall stocks coincides with BSI stocks that spawn in August. Figure 1c illustrates the Pacific coast populations' migratory paths and limits by combining the migratory data and pattern suggested by Felin (1954). The migration range may be influenced by the size structure of each subpopulation and controlled by ocean temperature (See Parrish and McFarlane papers in this symposium).

ADDRESSING POPULATION STRUCTURE

If subpopulations differ in productivity, the stock with higher productivity could induce overharvest of the other stock if a common quota is used. Even if their productivities are similar, asynchronous recruitment could result in strong recruitment to one stock, leading to overfishing of the other stock. This is especially important in contiguous stocks because markets and fleets can be redeployed causing "domino" collapse. Even shoreside plants can be involved, as was the case following the decline of the Pacific stocks after 1958 when the GOCAL sardine harvest was iced and trucked 500 km overland to idle canneries in Ensenada[5].

Given the contemporary lack of understanding of the sardine stock, the first priority is to exercise precautionary management to protect the regional stocks near all fishing ports. This policy should be implemented even before knowledge is gained of the essential details of the current geographic structure and seasonal migrations of the stock.

The second priority is to study the contemporary intermixture, if any, of sardines among the fishing areas around major ports. As a starting point, the boundary between the CCO and BSI stocks should be documented relative to the harbors of Ensenada and San Pedro. These efforts should be model driven (see Parrish this symposium) and prioritized by the level of fishing relative to the existing fishery management plan of the U.S. and the developing fishery management plan of Mexico.

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[3] H. C. Godsil. 1932. Untitled manuscript. Available at: Southwest Fisheries Science Center Library, 8604 La Jolla Shores Drive, La Jolla, CA 92038.

[4] O. E. Sette (deceased). 1935. unpub. ms.

[5] R. S. Wolf (retired), pers. comm.

TABLE 1
Sardinops **blood type frequency 1958–1962**

Site	L[a]	D[b]	N[c]	N C+[d]	%C+	Subpop.	Reference
Monterey, CA	36	−222	150	18	12.0	North	Sprague & Vrooman 1962
Morro Bay	35	−111	147	22	15.0	North	Sprague & Vrooman 1962
San Pedro	34	0	145	16	11.0	North	Sprague & Vrooman 1962
San Pedro	34	0	98	15	15.3	North	Sprague & Vrooman 1962
Santa Cruz Island	34	0	88	10	11.4	North	Vrooman 1964
Catalina	34	0	98	18	18.4	North	Vrooman 1964
Catalina	34	0	99	14	14.1	North	Vrooman 1964
San Pedro	34	0	100	6	6.0	South	Vrooman 1964
San Diego	33	111	110	12	10.9	North	Sprague & Vrooman 1962
San Diego	33	111	96	14	14.6	North	Sprague & Vrooman 1962
San Diego	33	111	184	7	3.8	South	Sprague & Vrooman 1962
San Diego	33	111	197	10	5.1	South	Sprague & Vrooman 1962
San Diego	33	111	100	15	15.0	North	Vrooman 1964
San Diego	33	111	56	7	12.5	North	Vrooman 1964
San Diego	33	111	247	34	13.8	North	Vrooman 1964
San Diego	33	111	140	18	12.9	North	Vrooman 1964
Del Mar	33	111	99	14	14.1	North	Vrooman 1964
San Diego	33	111	80	13	16.3	North	Vrooman 1964
San Diego	33	111	99	12	12.1	North	Vrooman 1964
San Diego	33	111	100	11	11.0	North	Vrooman 1964
San Diego	33	111	98	12	12.2	North	Vrooman 1964
San Diego	33	111	86	11	12.8	North	Vrooman 1964
San Diego	33	111	98	13	13.3	North	Vrooman 1964
San Diego	33	111	98	13	13.3	North	Vrooman 1964
San Diego	33	111	94	5	5.3	South	Vrooman 1964
San Diego	33	111	100	8	8.0	South	Vrooman 1964
San Diego	33	111	292	21	7.2	South	Vrooman 1964
Ensenada	32	222	100	12	12.0	North	Sprague & Vrooman 1962
San Quintin Bay	30	444	41	8	19.5	North	Sprague & Vrooman 1962
San Quintin	30	444	100	5	5.0	South	Vrooman 1964
Blanca Bay	29	556	74	6	8.1	South	Vrooman 1964
Vizcaíno Bay	28	667	100	5	5.0	South	Sprague & Vrooman 1962
Vizcaíno Bay	28	667	99	6	6.1	South	Sprague & Vrooman 1962
Vizcaíno Bay	28	667	105	7	6.7	South	Sprague & Vrooman 1962
Vizcaíno Bay	28	667	100	5	5.0	South	Vrooman 1964
Magdalena Bay	25	1000	151	7	4.6	South	Sprague & Vrooman 1962
Magdalena Bay	25	1000	100	6	6.0	South	Sprague & Vrooman 1962
Magdalena Bay	25	1000	100	7	7.0	South	Vrooman 1964
Magdalena Bay	25	1000	99	7	7.1	South	Vrooman 1964
Cresciente Island	24	1111	199	13	6.5	South	Vrooman 1964
Agua Verde Bay	25	1667	101	14	13.9	Gulf	Vrooman 1964
Mangles Point	26	1778	95	16	16.8	Gulf	Vrooman 1964
Carmen Island	26	1778	100	16	16.0	Gulf	Vrooman 1964
Carmen Island	26	1778	98	12	12.2	Gulf	Vrooman 1964
San Pedro Bay	28	2000	95	18	18.9	Gulf	Vrooman 1964
Los Animas Bay	28	2000	97	16	16.5	Gulf	Vrooman 1964
San Francis. Bay	28	2000	53	10	18.9	Gulf	Vrooman 1964
Puertecitos	31	2334	99	21	21.2	Gulf	Vrooman 1964

[a] degrees north latitude
[b] nominal km from San Pedro, CA by sea into Gulf of California
[c] numbers of fish processed
[d] numbers of fish with C+ reaction

Finally, harvest guideline (HG) models with separate biomass estimates should be implemented as in Conser et al. (2004) each year for each putative stock. Their parameters need to be based on new geographic boundary simulations, possibly with SIO (Scripps Institution of Oceanography) pier temperatures augmented, or replaced, by temperatures chosen from different locations.

A separate management model is required for each stock (in the notation used by the Coastal Pelagic Species plan[6] for sardine):

$$\text{HGa} = (\text{BIOMASSa} - \text{CUTOFFa}) \bullet \text{FRACTIONa} \bullet \text{USA DISTRIBUTIONa} \tag{1}$$

$$\text{HGb} = (\text{BIOMASSb} - \text{CUTOFFb}) \bullet \text{FRACTIONb} \bullet \text{USA DISTRIBUTIONb} \tag{2}$$

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[6] PFMC (Pacific Fishery Management Council). 1998. Amendment 8 to the Northern Anchovy Fishery Management Plan incorporating a name change to: The Coastal Pelagic Species Fisheries Management Plan. Pacific Fishery Management Council, Portland, OR 97220.

where HG is the harvest guideline; BIOMASS is the annual estimate of spawning biomass in tons; CUTOFF is the threshold biomass below which no fishing occurs; FRACTION is a value between 0.05 and 0.15 based on temperature at Scripps Pier; and USA DISTRIBUTION is the proportion allocated to U.S. fishermen.

The current harvest guideline is derived from studies of early (1930–90) catches and estimated biomass (Jacobson and MacCall 1995). Jacobson and MacCall (1995) performed simulations assuming a single stock north of Punta Baja, Baja California Norte. The criterion for CUTOFF was that the stock should be able to recover rapidly from a series of recruitment failures. FRACTION was a value that would minimize the frequency of collapses during cold and warm phases of the California Current region. The USA DISTRIBUTION value is arbitrary. To successfully implement the pair of models, the seasonal geographic location and biomass estimates of all subpopulations must be approximated with respect to the fishery from each port. The criteria, productivity, and variability used for simulation would have to be established with new parameters and latitudinal ranges for each of the proposed stocks.

DATA FOR MANAGING SARDINE STOCKS

The geographic location and extent of the stocks' seasonal spawning areas should be monitored frequently. The fishery only exists in the coastal region of the sardines' total distribution. There may be insufficient data on fisheries landing catches at Cedros Island or directly at tuna-rearing pens along this stretch of coastline. Historical information on length-at-age, vertebral count, temperature, and season-of-capture may suffice for allocating catches for current management purposes.

Techniques for obtaining environmental parameters from research ships and space (Lynn 2003), and obtaining egg samples and surface salinity from ships underway at full speed, should be given priority for development, because the current sardine fleet would not be useful for the long-range requirements of establishing boundaries of spawning grounds. The boundaries of spawning biomass can be monitored in the peak spawning seasons using egg-pump surveys. When the stocks overlap, spawning biomass can be estimated from Punta Eugenia to Alaska in April for the CCO stock and from Point Conception south to the tip of Cape Lucas in August for the BSI stock. If the GOCAL stock is to be managed at the same time as the BSI and CCO stocks, the initial spawning area surveys should be from Cape San Lucas to the northern margin of the GOCAL in November–January (Moser et al. 1993; Aceves-Medina et al. 2004). While index methods may suffice for management, these biomass values should be validated periodically by daily egg production methods (Lasker 1985) using adult and area egg production methods. Adult sampling conducted to determine egg production should include analysis of vertebral counts, otolith determinations of trace metals, growth, and season of birth.

Blood type analysis is probably not feasible for monitoring racial boundaries, and current genetic approaches can barely distinguish between sardines in the far-flung reaches of the Pacific and Indian Oceans (Hedgecock et al. 1989; Parrish et al. 1989; Grant and Leslie 1996; Bowen and Grant 1997; Grant and Bowen 1998; Lecomte et al 2004). Thus, the development of genetic techniques is a necessity.

At the time of egg production assessment, scientific sampling for genetic analyses should be instituted. Current genetic studies are hampered by a number of factors; many have used specimens collected haphazardly by volunteers, and these are geographically biased because volunteer collectors do most of their collecting near the coast. Compared with the definitive vertebral count studies and erythrocyte antigen studies (Vrooman 1964; Wisner 1980), existing genetic studies may have used insufficient numbers of fish to define within-region stock boundaries.

Representative genetic samples should be allocated by use of the seasonal and spatial distribution of egg-pump samples. As a matter of priority, fisheries in the area where stock migrations overlap—San Pedro to Ensenada—could be studied more intensely in April and August. Existing data (tab. 1) on blood types (Sprague and Vrooman 1962; Vrooman 1964) and vertebral counts (tab. 2; fig. 2) (Wisner 1960) should serve to design the quantitative genetics work (Sprague and Vrooman 1962; Vrooman 1964) rather than the small number of specimens used by Hedgecock et al. (1989) and Lecomte et al. (2004).

STANDARDS FOR DEFINING FISHERY STOCK GENETICS

In his classic review of fishery biochemical genetics, Utter (1991) restated the logical principle that "absence of proof is not proof of absence."

> . . . it is important to note that differences in frequencies between collections of individuals sampled from distinct locations or at different times are usually reliable evidence for genetic differentiation between the sampled populations . . . the absence of such differences is not in itself positive evidence that the samples were drawn from a single panmictic population.

The works of Rodriguez-Sanchez et al. (2002) and Lecomte et al. (2004) support a major alternative to the established three-stock idea. For example, it is possible that the immuno-genetic approach to stock definition

TABLE 2
Pre- and Post-Sardine Collapse Vertebral Count

Precollapse (Clark 1947)

Collection Area	Sea km from San Pedro	Number of Fish	Number of Fish >51	Proportion Fish >51	Std Error	Lower 95% Limit	Upper 95% Limit
Gulf of California	1713	735	121	0.165	0.027	0.138	0.191
Magdalena Bay	1296	795	250	0.314	0.032	0.282	0.347
Pta. Eugenia-CSLaz	963	710	261	0.368	0.035	0.332	0.403
Sebastian Vizcaino Bay	741	1093	651	0.596	0.029	0.567	0.625
San Diego	148	6553	4380	0.668	0.011	0.657	0.680
San Pedro	0	9652	6490	0.672	0.009	0.663	0.682

Postcollapse (Wisner 1960)

Collection Area	Sea km from San Pedro	Number of Fish	Number of Fish >51	Proportion Fish >51	Std Error	Lower 95% Limit	Upper 95% Limit
Gulf of California	1713	611	122	0.200	0.032	0.168	0.231
Magdalena Bay	1296	679	209	0.308	0.035	0.273	0.343
Santa Maria Bay	1204	842	314	0.373	0.033	0.340	0.406
Pta. Eugenia-CSLaz	963	1967	849	0.432	0.022	0.410	0.454
Sebastian Vizcaino Bay	741	559	234	0.419	0.041	0.378	0.460
Cedros San Benito	685	783	417	0.533	0.035	0.498	0.568
Ensenada	269	10670	5325	0.499	0.009	0.490	0.509
San Diego	148	666	343	0.515	0.038	0.477	0.553
San Pedro	0	1864	940	0.504	0.023	0.482	0.527

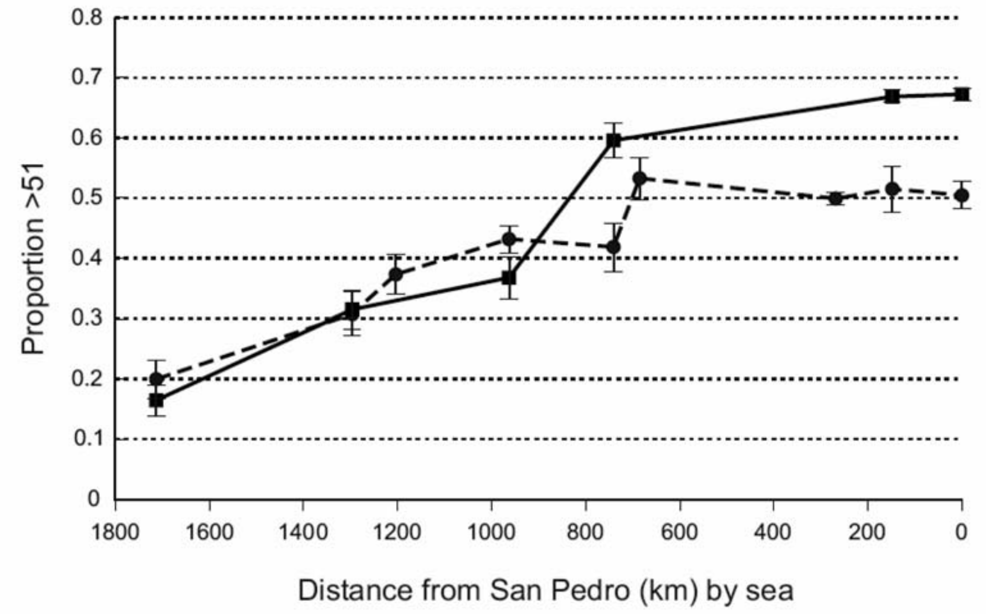

Figure 2. Geographic position of a postulated internal range boundary derived from a comparison of the latitudinal gradient of vertebral fractions ($p > 51$) from before the Pacific sardine (*Sardinops sagax*) fishery collapse (solid line) and after the fishery collapse (dashed line).

is not able to isolate the genetic/environmental balance of controls[7]. It is possible that the CCO stock was so reduced that it has now been replaced from a migrant BSI stock. Hedgecock et al. (1989), however, discounted the idea that the recent decline of sardines was evidence of an evolutionary bottleneck.

Simulations of the CCO stock (Gaggiotti and Vetter 1999) also indicate that it is unlikely that the genetics of the putative CCO stock were reduced in biomass enough to have become a genetic "bottleneck."

The use of vertebral counts appears to be a robust, if tedious, method for distinguishing the BCS and CCO stocks. Data on vertebral counts are available for the 1900s. Wisner (1960) plotted the results from two periods: before the collapse of 1921–41 and after the collapse of 1951–59 (fig. 2). From the comparison of collection

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[7] W. S. Grant. 2004. pers. comm. P.O.Box 240104, Anchorage, AK 99524.

sites, the two lines appear to diverge north of Sebastián Vizcaíno Bay; this latitudinal cline was expected based on analysis of temperature data. This suggests that the underlying rate of increase of vertebral count distribution is a function of temperature at birth, and the two lines may result from genotypic differences as in the case of the coincident blood types. The genetic origin of vertebral count distribution has been illustrated by experiments on Atlantic silverside (*Menidia menidia* (L.))[8].

The few contemporary vertebral counts off Southern California (61.5%) and Oregon (Survey 76.5%; Fishery 69.2%)[9] estimate the percentage of vertebral counts at or above 52. If the South Baja inshore stock had invaded the coast from Central California to Alaska, one would expect fewer vertebrae than those found in the 1950s. Birth date determination by daily otolith ring counting indicates that as many sardines were born in August as in April in San Diego waters in 1982–83 (Butler 1987). The putative northern stock declined to less than 10,000 tons for the period between 1964 and 1980 (fishing moratorium 1967–84). The southern stock near Magdalena Bay was not diminished in this period according to juvenile bait fish estimates of population size and geographic distribution analyzed by Rodriguez et al. (2002). The failure of the southern stock to fill in for decades after the virtual disappearance of the northern stock militates against the deregulation of fisheries based on hope that a stock decline can be rectified by migration from adjacent habitats (Taylor and Dizon 1999). Lastly, in a comprehensive study of sardine and anchovy fisheries (Jacobson et al. 2001), it was found that the instantaneous natural mortality rates ranged from 0.7 for GOCAL and BSI stocks to 0.4 for the CCO stock; this difference alone would require separate management models irrespective of whether the stocks are separated on habitat or genetic bases.

SUMMARY

The sardines (*Sardinops sagax*) of the northeast Pacific have been referred to as three subpopulations based on tagging (Clark 1947), size-at-age (Felin 1954), isolated spawning centers (Marr 1960), blood groups (Vrooman 1964), vertebral column count (Wisner 1960), estimated natural mortality rate (Murphy 1966; MacCall 1979; Jacobson et al. 2002), or bimodal seasons of recruitment (Butler 1982)[10]. Spawning centers are in the Gulf of California (GOCAL), Baja California Sur inshore (BSI) and Central California Offshore (CCO). Cursory genetic examination of sardines from these areas neither supports nor refutes these divisions (Hedgecock et al. 1989; Lecomte 2004). Studies to date are considered cursory because the sardine geographic areas and boundaries have not been contemporarily, systematically, and representatively sampled. Genetic analysis of *S. sagax* from four far-flung sardine habitat sectors of the Pacific basin can be described as "shallow," (Parrish et al 1989; Grant and Bowen 1998) meaning that the separation of all the species in the Pacific is relatively recent. However, on the time scale of fisheries management, decades, the separation of the stocks appears chronic in that the virtual collapse of the northern stock, 1940–79, did not stimulate an apparent replacement from the southern stock in decades. Therefore, it would be prudent to institute separate management measures defining the boundary between GOCAL and BSI and the boundary between BSI and CCO regardless of the genetic or habitat basis for stock separation. Three data-rich bases for describing stocks' modern isolation should be used to design careful studies of representative samples of sardines at the boundaries between the stocks for devising the most practical method for allocating catches among the neighboring stocks.

A review of the literature characterizing sardine catch and fishery independent samples of eggs and adults lends support for the continued existence, at important times, of isolated subpopulations of sardines in the northeast Pacific. That panmixia existed, on the other hand, has been concluded from cursory examination of regional genetic characteristics and is likely based on flawed logic; absence of evidence is not evidence of absence of subpopulation structure. It appears that historical data on blood types, vertebral counts, and spawning areas would serve to design practical approaches to determining the contemporary distribution of sardine stocks in this region.

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[8] Methodological Note: The original analyses of vertebral count used analysis of variance on a distribution composed of six integer values (49–54 vertebrae) with leptokurtic deviations from normal distribution. While these analyses and frequencies are published, I have chosen to treat the vertebral counts as two categories: greater than 51 and less than or equal to 51 vertebrae expressed as a fraction. This separation near the median allows precise binomial descriptions of the proportions and a normal approximation of confidence limits (fig. 2; tab. 2). It is easier to envision differences in proportions r than differences in averages which differ by only hundredths of a vertebra.

[9] D. Ambrose. 2004. pers. comm. NOAA/NMFS/SWFSC, 8604 La Jolla Shores Dr., La Jolla, CA 92037.

[10] H. C. Godsil. 1932. Untitled manuscript. Available at: Southwest Fisheries Science Center Library, 8604 La Jolla Shores Drive, La Jolla, CA 92038.

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RELATIONSHIP OF CALIFORNIA SARDINE (*SARDINOPS SAGAX*) ABUNDANCE TO CLIMATE-SCALE ECOLOGICAL CHANGES IN THE CALIFORNIA CURRENT SYSTEM

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ABSTRACT

Empirical orthogonal function (EOF) analyses link sardine abundance to large-scale processes of the California Current ecosystem. These analyses of the California fish and invertebrate landings (CACom) detect two patterns of variability (EOF1 and EOF2), which indicate that climate-scale changes in CACom species composition occurred during 1930–2000. California sardine landings are related to EOF1 (nominal correlation coefficient, $r' > 0.9$), linking fluctuations in sardine abundance to many other California Current species. Log_e-transformed sardine landings are closely related ($r' > 0.9$) to accumulated sea surface temperature anomalies at La Jolla, California and to accumulated equatorial process indices ($r' \geq 0.8$). We found that the length of time that physical anomalies persist is related exponentially to the effects these physical processes will have on sardine abundance. When the sardine series is extended backward to 1890, using sardine-scale deposition rates as an abundance proxy and the equatorial indices as physical proxies, the relationships between sardine abundance and the physical environment holds ($r' \geq 0.8$).

INTRODUCTION

The abundance of California sardines, or pilchards, (*Sardinops sagax*) off the west coast of temperate North America fluctuates, and in the 1930s and 1940s sardine populations were the source of the largest fishery of the western hemisphere (Marr 1960; Jacobson and MacCall 1995; Norton and Mason 2003). The largest landings of sardines were in California ports, where shore-based landings exceeded 400,000 metric tons (t) in each year from 1934 to 1944. California sardine populations declined sharply in the later 1940s and continued to decline into the early 1970s when annual landings were less than 10 t (Mason 2004). In 1967, a moratorium was placed on the directed California sardine fishery, but 15% by weight was allowed in mixed-species landings. In 1969, landings for dead bait were limited to 227 t, and in 1974 recovery plans were developed to allow a directed fishery of 907 t when the California spawning population was estimated to be more than 18,144 t. Increases in the harvest quota would be allowed if the spawning population continued to increase (Conser et al. 2004). In the late 1970s and 1980s, the California sardine population increased due to environmental changes (Jacobson and MacCall 1995), and their landings increased from 388 t in 1986 to more than 56,000 t in 1999 and 2000 (Mason 2004).

California state laws require that all sales of fish and invertebrates from primary harvesters (fishers) to fish dealers include the species (or species groups) and weight landed on the sales receipts. The summaries of these sales receipts for catches within the California Fishers Harvest Environment (CFHE), tabulated by the California Department of Fish and Game, were converted to Internet accessible formats by the Pacific Fisheries Environmental Laboratory (http://www.pfeg.noaa.gov/products/las.html). These records (CACom) provide information about the availability of the commercially important components of the California Current System (CCS) ecosystem (Norton and Mason 2003, 2004).

Empirical Orthogonal Function (EOF) analysis of these records showed that EOF1 and EOF2 explained more than 45% of the variance in composition of 29 species that made up more than 85% of the total CACom landings throughout the 1930–2000 period. When time-varying coefficients (principal components) of these EOFs, C1 and C2, were compared to indices of physical change in the CFHE and to time series representing fishing effort and market factors, they were found to be more closely correlated to the environmental indices than to fishing effort or market indices. Landings composition changes shown by C1 were closely related to persisting anomalous conditions in the CFHE as indicated by several physical environmental data series, including sea surface temperature (SST) measured at La Jolla, California (Norton and Mason 2003).

The purpose of this study is to investigate the relationship of sardine landings to the physical and biological environments of the CFHE, which is that part of the CCS extending from the coast of California to 400–600 km offshore between 32.5° and 42°N latitude (Norton and Mason 2003). We build on the observations that the $\log_e$ of California sardine landings weight is strongly related to C1 (Norton and Mason 2004) and that sardine abundance in the CFHE may be indexed by SST at La Jolla, California (Marr 1960; Jacobson and MacCall 1995; MacCall 1996; and Norton and Mason 2003, 2005). We also use proxy sardine abundance records and reconstructed physical variables to investigate the relationship between physical and biological parameters in the late 1800s, before the development of the industrial sardine fishery. Anchovy abundance series are examined to show that they differ significantly from sardine landings series throughout the 1900s.

METHODS

The 29 species selected for analysis (tab. 1) were: 1) identified unambiguously by species in the landings records and 2) recorded in the catch in 60 or more of the 71 years studied (Norton and Mason 2003, 2005). Each of the 29 single-species landings records from 1930 through 2000 was $\log_e$-transformed and placed as a column-vector in the data (input) matrix. The corresponding correlation matrices were formed from the data matrix and eigenvectors (proportional to empirical orthogonal functions or EOFs), and eigenvalues of the correlation matrix were computed (Norton and Mason 2004). Only EOF1 and EOF2, which 1) explain the most and second-most variance of the input matrix and 2) are significant at less than the 0.05 level (North et al. 1982), are discussed in this report. The products of the EOFs and the corresponding data matrix give the time-variable coefficients (Cn, n = 1, 2) and indicate the variation of each unique EOF through the 1930–2000 period. Each column (species) has a loading value within the EOF. The magnitude of the loading value indicates the relationship between the time variation in Cn and the time variation of that species (see below). Each Cn-series represents a mode of temporal variation characteristic of the data matrix.

Indices of climate-scale physical environmental change were derived by taking anomalies from overall time-series means. The anomaly series, X, was accumulated (integrated) through time,

$$A - X(y) = \sum_{i=b}^{y,} X(i), \tag{1}$$

where $A - X(y)$ is the accumulation of the anomaly time series X, b is the first year of the accumulation, and y is a year between b and 2001. The accumulated series may be interpreted in terms of processes that, together, cause negative or positive anomalies (Klyashtorin 2001; Hanley et al. 2002; Norton and Mason 2003, 2004). The length of the trend indicates the time period of persistent anomaly, and the rise of the trend indicates the magnitude of the anomalous integrated period. Seasonal and many interannual events may be attenuated in these integrated indices, making accumulated series valuable for illustrating climate-scale (8–30 years) changes. These anomaly accumulation methods (Equation 1) were used to derive the first six of the eight index series described below.

First, the La Jolla A-SST climate index is derived from monthly mean SST taken at the Scripps Institution of Oceanography pier in La Jolla, California (32.9°N, 117.3°W). These SST data are available from <ftp://ccsweb1.ucsd.edu/pub/shore>.

Second, the A-SWS (southward windstress) climate index was computed for an area off Central California with consistently large numbers of observations in the Comprehensive Ocean-Atmosphere Data Set (COADS). This area is bounded by the California coast and 39°N, 124°W; 37°N, 124°W; 37°N, 123°W, and 36°N, 123°N (Parrish et al. 2000; Norton and Mason 2003). By convention, greater SWS is indicated by larger magnitude negative index values.

Third, the A-DSLP sea-level atmospheric pressure index for Darwin, Australia (12.4°S, 130.9°E) is related to El Niño-like physical events in the equatorial and CFHE regions (Norton and McLain 1994; Alexander et al. 2002; Fu and Qui 2002). Darwin SLP is available from Kousky (2003) at <http://www.cpc.ncep.noaa.gov>.

Fourth, the A-JMA index was computed from the average equatorial SST anomaly from the area defined by 4°N to 4°S, 150°W to 90°W and known as the JMA ENSO index (Hanley et al. 2002). It is available at <http://www.coaps.fsu.edu/~legler/jma_index1.shtml>.

Fifth, the A-NINO3.4 climate index was formed by accumulating deviations from the linear trend of SST anomalies in the NINO3.4 area (5°N to 5°S, 170°W–120°W). Kaplan et al. (1998) used the United Kingdom Meteorological Office historical SST data set, optimal interpolation, and other statistical techniques to reconstruct the major features of the global SST field from 1856–1991. Updated data are available from <http://ingrid.ldeo.columbia.edu/SOURCES/.Indices/.nino/.EXTENDED/>.

Sixth, the Palmyra A-cST was calculated from a 1860–1998 temperature time series derived from cores of living and fossil coral at Palmyra Island (6°N, 162°W), about 100 km north of the NINO3.4 area. This series is included because these proxy records appear to give annual measurements of shallow water sea temperature (Cobb and Charles 2001; Cobb et al. 2003). The coral record is independent of the NINO3.4 reconstruction and potentially provides estimates of sea temperature extending centuries into the past (Cobb and Charles 2001; Cobb et al. 2003). These data are available from <http://www.ngdc.noaa.gov/paleo/pubs/ cobb2003/>. Palmyra A-cST, was formed by accumulating deviations from a linear trend.

Seventh and eighth, estimates of sardine and anchovy abundances from 1850–1970 were obtained from scale-deposition rates (SDRs) in the anaerobic sediments of the Santa Barbara Basin (34.25°N, 120.09°W). Soutar and Isaacs (1974) found that these SDRs were proportional to estimates of sardine and anchovy biomass. We used the SDRs per 1000 cm^2 yr^{-1} averaged for 10-year periods (fig. 4 in Baumgartner et al. 1992,). All sardine and anchovy series are $\log_e$-transformed and, like C1 and C2, may reflect the integration of environmental anomalies, but they are not accumulated or integrated variables.

Landings Abundance and Biomass Estimates

To examine the relationship between California landings and biomass estimations for the entire West Coast stock, we compared estimated biomass for one-year-old and older fish (Conser et al. 2004) to records of sardine landings in California ports (Norton and Mason 2003; Mason 2004) for the 1932–2000 period. When each series was $\log_e$-transformed, there was a high degree of similarity between them (the nominal correlation coefficient, $r' = 0.88$). Correlation between the transformed estimated biomass and landings series was $r' = 0.77$ for the largely unregulated 1932–63 period and $r' = 0.97$ for the regulated 1983–2000 period. The major differences in the 1932–63 records occur during events shorter than eight years. The transformed landings values for the 1983–2000 period are expected to vary with the transformed biomass estimates, since landing quotas were directly dependent on biomass estimations (Conser et al. 2004). The low-abundance 1964–82 years were not included in the correlation analysis because biomass estimations are not available for this period (Jacobson and MacCall 1995).

All time series are graphed and manipulated as standardized variables (Is),

$$Is = (S - Ms) / SDs, \qquad (2)$$

where S is a discrete value in series s, Ms is the mean of s. and SDs is the standard deviation of s.

Relationships between physical and biological variables were examined graphically and by simple correlation. All correlations were tested for effective degrees of freedom (n), determined by the long-lag (20%–30%) correlation method (Chelton 1983). Herein, correlation coefficient magnitudes larger than 0.8 ($|r| > 0.8$) test by n to occur by chance at a rate of less than one in 20 trials ($p < 0.05$), but caution should be applied to this interpretation. A persisting problem with climate research on modern data is that it is undertaken with series of only a hundred-years, and any phenomena investigated will have few repetitions. The prospect for hypothesis testing using common statistical techniques is limited for these data (von Storch and Navarra 1995). Consequently, the correlation coefficients (r'-values) are to be considered primarily as comparative statements, rather than as consistently suitable for statistical interpretation.

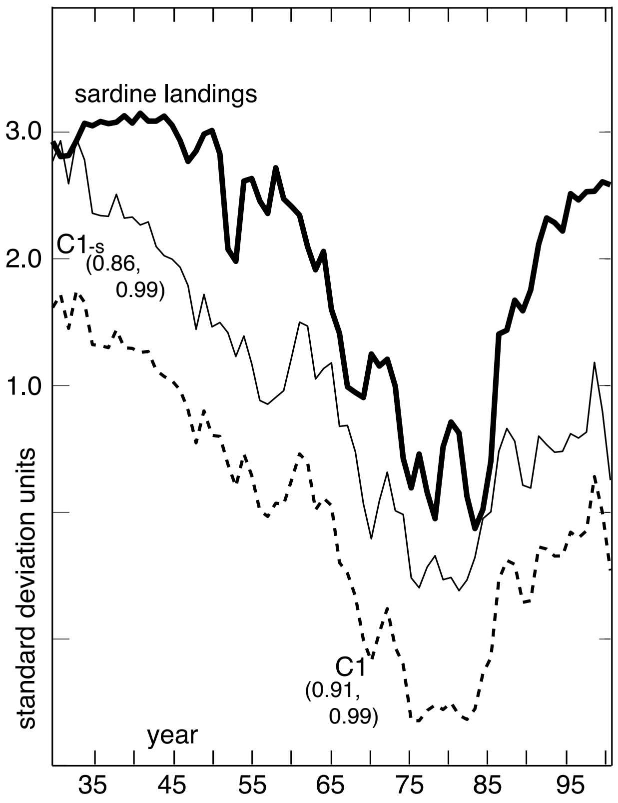

Figure 1. Sardine landings variability through the 1930–2000 period is shown by the upper, heavy line. The lower, broken line gives C1, the time variation of EOF1, derived from 29 species. The middle series, C1-s, is the same as C1 except the sardine series has been omitted from the computation (solid line). Correlation to the sardine series is given first in parentheses, and the correlation with the other variable second. C1 is closely related to the sardine landings series ($r' = 0.91$) and is nearly independent of the sardine landings series. All series are standardized and offset for comparison.

RESULTS

The total catch of sardines during 1930–2000 exceeded 8 million t and was close to the catch of all other species combined. Therefore, it might be expected that the sardine landings pattern would dominate the time variation in C1. However, this is not the case (fig. 1), because C1-s computed without the sardine series is nearly identical to C1 computed with the sardine series. Both are similar to the sardine series ($r' > 0.85$), indicating that many of the other 28 species used in calculating C1-s are affected either positively or negatively by the same environmental factors that affect sardine abundance (fig. 1).

Species Associations

Each of the 29 species used to calculate EOFs had periods of relatively high landings (maxima) during the

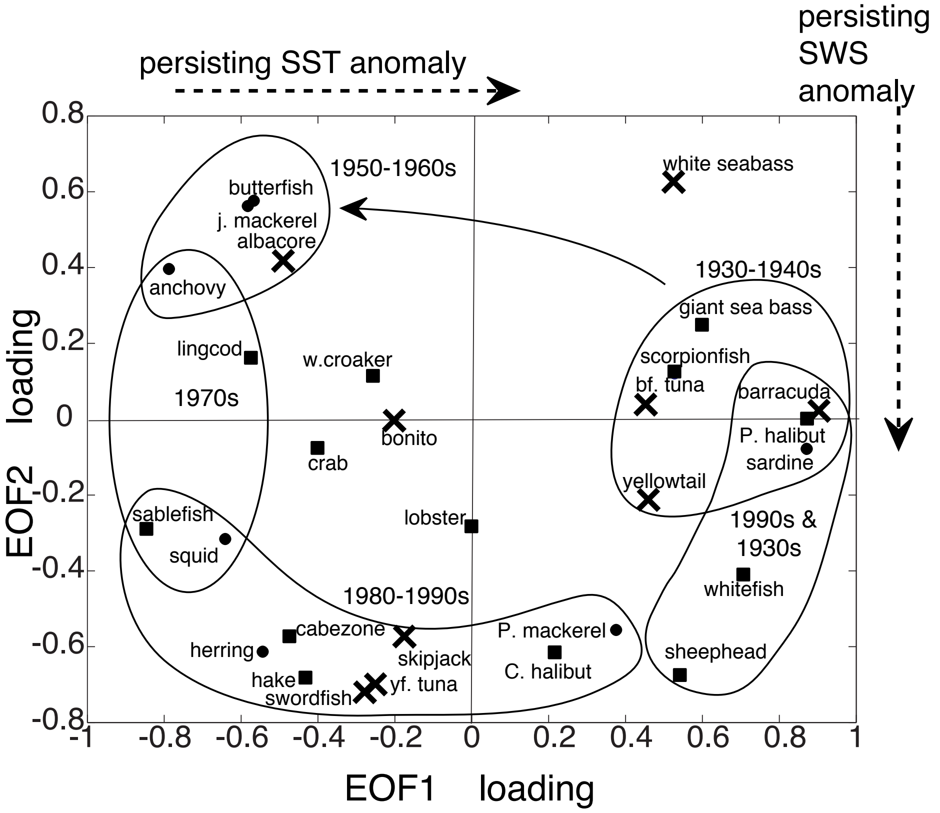

Figure 2. Loading values are plotted for EOF1 on the horizontal and for EOF2 on the vertical axes. The enclosed species-groups show the counter-clockwise progression of species having landings maxima. Filled squares show species that are harvested from demersal habitats. Crosses indicate migratory species that are also found outside the California fishers harvest environment (CFHE), and filled circles indicate species harvested from pelagic habitats. Shifts in availability and harvest of the 29 species caught throughout the 1930–2000 period show the ecological climate signal. The dotted arrow at the top shows the shift in CFHE species composition as positive SST anomalies accumulate. The dotted arrow on the right side shows the shift in species composition as southward wind stress off California continues to be anomalously strong. By convention, southward wind stress is negative. Complete species names are given in Table 1.

1930–2000 period. The temporal distribution of characteristic species-group maxima is shown in Figure 2 (enclosed), where EOF1 loading values for each species are plotted on a horizontal axis, and EOF2 loading values are plotted on the vertical axis. Sardines, scorpionfish, barracuda, and yellowtail and Pacific mackerel were all at or near their landings maxima during the 1930s and 1940s (center right in fig. 2). Jack mackerel and albacore were near their maximum landings in the 1950s and 1960s (upper left). Anchovy and sablefish were near their maximum abundance in the landings during the 1970s (center left). Skipjack, yellowfin tuna, swordfish, hake, and Pacific mackerel were at their maximum landings during the 1980s and 1990s (lower center). A cycle appears to have completed in the 1990s (lower, right) with sheephead, whitefish, and sardines increasing in abundance. While commercial landings of barracuda and white seabass were low because of extensive regulation during the 1990s, recreational catches of barracuda and white seabass increased through this warmer period. These changes in species-group maxima may indicate repeating changes in the flow of productivity (renewable food energy initially provided by photosynthesis) through the web of CCS ecological processes.

Each of the 29 species shown in Figure 2 is categorized by capture habitat: demersal, migratory, or pelagic (tab. 1). These groups are not entirely exclusive. The distribution of each habitat group through each quadrant and into four of the five species-groups (enclosed in fig. 2) shows that the climate effects found in the landings series are wide-spread in the CFHE and not limited to specific habitats.

Physical Forcing

Studies have shown that C1 is related to the large-scale patterns of physical variation that are monitored by the SST at the Scripps Institution of Oceanography pier (La Jolla) in southern California and by equatorial indices of climate variation (Norton and Mason 2003, 2004). The implication of these large-scale relationships (fig. 3) is that in the absence of mid-latitude indices, equatorial indices are suitable for monitoring the same

TABLE 1
Harvest Habitat for 29 Species Recorded in California Landings 1930–2000

Demersal	n[a]
California (C) halibut[b]	*Paralicthys californicus*
cabezon	*Scorpaenichthys marmoratus*
crab	*Cancer magister*
white (w) croaker	*Genyonemus lineatus*
giant sea bass	*Stereolepis gigas*
hake	*Merluccius productus*
lingcod	*Ophiodon elongatus*
lobster	*Panulirus interruptus*
Pacific (P) halibut	*Hippoglossus stenolepis*
sablefish	*Anoplopoma fimbria*
scorpionfish	*Scorpeaena guttata*
sheephead	*Semicossyphus pulcher*
whitefish	*Caulolatilus princeps*
Migratory[c]	✖
albacore	*Thunnus alalunga*
barracuda	*Sphyraena argentea*
bluefin (bf) tuna	*Thunnus thynnus*
bonito	*Sarda chiliensis*
skipjack	*Euthynnus pelamis*
swordfish	*Xiphias gladius*
white seabass	*Atractoscion noblis*
yellowtail	*Seriola dorsalis*
Yellowfin (yf) tuna	*Thunnus albacares*
Pelagic	c
anchovy	*Engraulis mordax*
butterfish	*Peprilus simillimus*
herring	*Clupea pallasi*
Jack (j) mackerel	*Trachurus symmetricus*
Pacific (P) mackerel	*Scomber japonicus*
sardine	*Sardinops sagax*
squid	*Loligo opalescens*

[a] Symbol used in Figure 2 for this harvest group.
[b] Naming conventions follow those of Miller and Lea (1972).
[c] Indicates species that migrate into the CFHE, but are not generally present throughout the year.

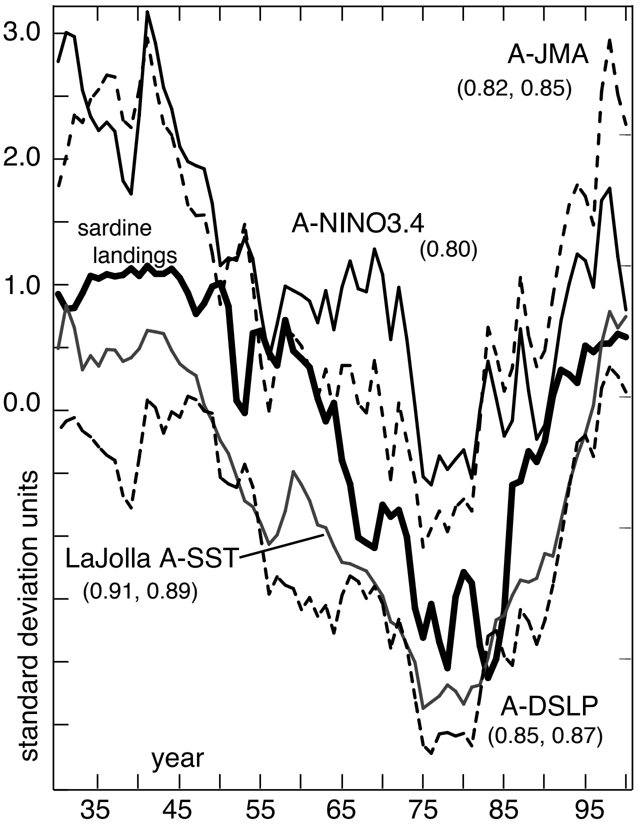

Figure 3. Comparison of sardine landings (heavy, solid line) to physical indices from southern California (La Jolla A-SST, lower, solid line) and the equatorial atmosphere-ocean system. Numbers in parenthesis show correlations first to the sardine series and second to the A-NINO3.4 series (upper, solid line). A-JMA (upper, broken line) and A-NINO3.4 represent the SST anomaly over large areas of the equatorial ocean (see Methods). A-DSLP is shown by the lower, broken line. All series are standardized and may be offset for clarity.

large-scale phenomena that appear to regulate sardine abundance and 30% of the variability in commercial fish landings from the CFHE.

Changes in La Jolla SST are correlated with 1000 kilometer-scale ocean events in the eastern temperate Pacific (Marr 1960; McGowan et al. 1998; Norton 1999). The Darwin sea-level pressure indexed by A-DSLP and the equatorial SST indexed by A-JMA and A-NINO3.4 are unambiguous representations of equatorial climate events. The remote climate signal is clearly represented within the CFHE by the La Jolla A-SST, which is more closely related to sardine abundance than the equatorial indices during 1930–2000. It is clear from Figure 3 that on climate scales of eight to 60 years, there is considerable correlation of physical variability ($r' \geq 0.80$) throughout the equatorial and northeastern Pacific, which is also correlated to sardine abundance.

If the CFHE sardine stocks are as extensively utilized and sampled as they were throughout most of the 1930–2000 period then,

$$\log_e (B) = f(s) \sum(A), \tag{3}$$

where B is the abundance measure in weight, A is the environmental process anomaly and $f(s)$ is a scaling function. Herein, $f(s)$ represents standardization (Equation 3). If the La Jolla A-SST, as shown in Figure 3, represents the right side of Equation 3, then its values would be the calculations of $\log_e$ sardine abundance (fig. 3, La Jolla A-SST), and the correlation between the observed (fig. 3, sardine landings) and calculated would be $r' = 0.91$ for the 1930–2000 period. Equation 3 expresses an exponential biological response, shown in sardine abundance and C1, to the processes represented by the accumulating anomaly.

Of the equatorial indicators, A-DSLP appears most closely related to sardine abundance ($r' = 0.85$). The A-JMA and A-NINO3.4 appear less closely related to sardine abundance ($r' \geq 0.80$), but the overall pattern of these two equatorial SST variables is similar to the others shown in Figure 3. The close correspondence in

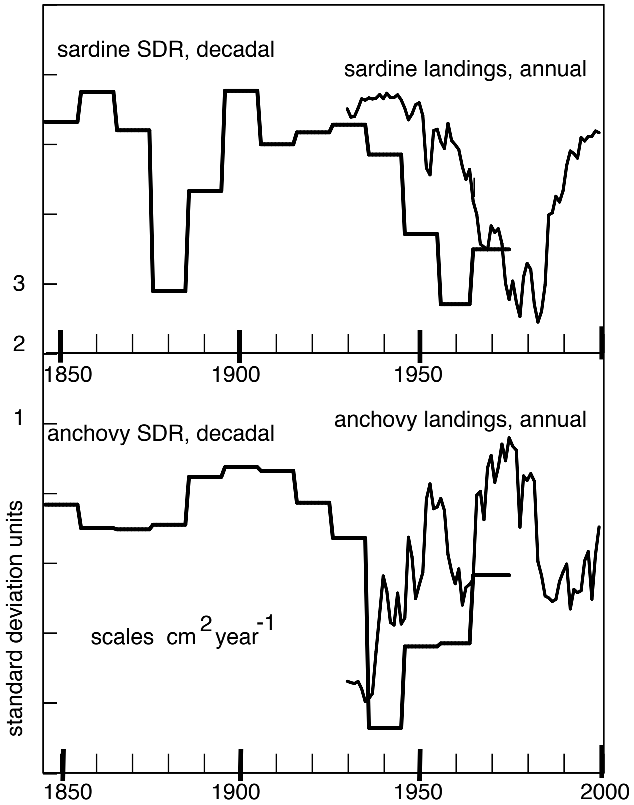

Figure 4. The upper panel shows comparison of sardine abundance estimates from scales (heavy, stepped line) and sardine abundance estimates from the California commercial landings (CACom). The lower panel compares estimates of anchovy abundance from scale deposition rates (SDR) with the CACom landings of anchovy. Each series is $\log_e$-transformed before standardization. Scale abundance estimates are from scale deposition rate in number of scales per 1000 cm^2 $year^{-1}$ (SDR).

turning points and the length of the periods of positive and negative anomaly (positive and negative slope) show that the decadal changes in the California Current region are basin scale and may be detected in equatorial processes. The A-JMA and A-NINO3.4 equatorial indices are rich in one to seven year (interannual) variability. Much of this variability is reflected one to four years later as fluctuations in sardine landings (e.g., 1950–56 and 1975–83 in fig. 3), suggesting an equatorial to CFHE influence on these timescales, as well as on climate scales that are the focus of this report.

Extending the Biological Series

Baumgartner et al. (1992; fig. 4) present time series from 500 to 1970 of sardine and anchovy abundance based on their scale-deposition rates (SDR) in the anaerobic sediments of the Santa Barbara Basin. If the sardine SDR can be used to examine how physical events correspond to sardine abundance, then SDR series provide comparisons that will be independent of previous tests based on the 1930–2000 CACom landings.

The decadal $\log_e$-transformed SDRs are compared to the annual $\log_e$-transformed sardine and anchovy landings in Figure 4. SDR series are centered on the decade indicator (e.g., 1940, 1950, etc.). Both sardine series show a decline in the 1930–70 period. The greatest rate of decline in sardine landings occurred during 1956–65, an interval when few sardine scales were deposited. After the sharp decline of the 1960s, there was a small increase in both sardine series, possibly related to the 1972–73 El Niño period when local reproduction and migration from the south were enhanced. For the anchovy series, there is an increase in landings in two steps through the 1930–70 period. Differences in lead-lag dynamics between the landings and scale sedimentation lead to the differences between the SDR and landings series (e.g., sardine in the 1930s, fig. 4). However, the general agreement between landings and SDR series (fig. 4) and the findings of Soutar and Isaacs (1974), who found proportionality between SDR and biomass estimates of sardine and anchovy for the 1930–58 period, indicate that the SDR series may be a usable proxy for CFHE sardine and anchovy abundance.

Extending the Physical Series

Four physical series are compared over their common ranges (fig. 5) to examine the possibility of extending the physical series backwards. The NINO3.4 reconstruction is the longest, extending from 1856 to the present. The Palmyra A-cST, A-DSLP, and La Jolla A-SST indices extend back from 2000 to 1886, 1890, and 1917, respectively (fig. 5). There is generally good agreement among the physical indices back to about 1910 (fig.5). A-NINO3.4 has greater amplitude variability causing divergence at several scales throughout the record. However, the phase of interannual events is similar in each series.

Scale Deposition Compared to Physical Variability 1890–1970

The equatorial indices, found to be reasonable proxies for CFHE climate processes, and the sardine SDR record of Baumgartner et al. (1992) are compared in Figure 6. The four physical series are fundamentally similar; they are different estimations of the same climate events detected at different locations. For clarity, the A-cST time series is not shown, but, for comparison, *r*'-values for A-cST appear in Figure 6 below the *r*'-values for A-DSLP.

The sardine-scale records approximate 10-year SDR averages (Baumgartner et al. 1992). The physical data represent annual estimates of climate-scale environmental processes. Generally, scale deposition and the physical environment were more correlated when compared by the center annual physical values (e.g., 1910, 1920, etc.) than when compared by averages of the ten annual

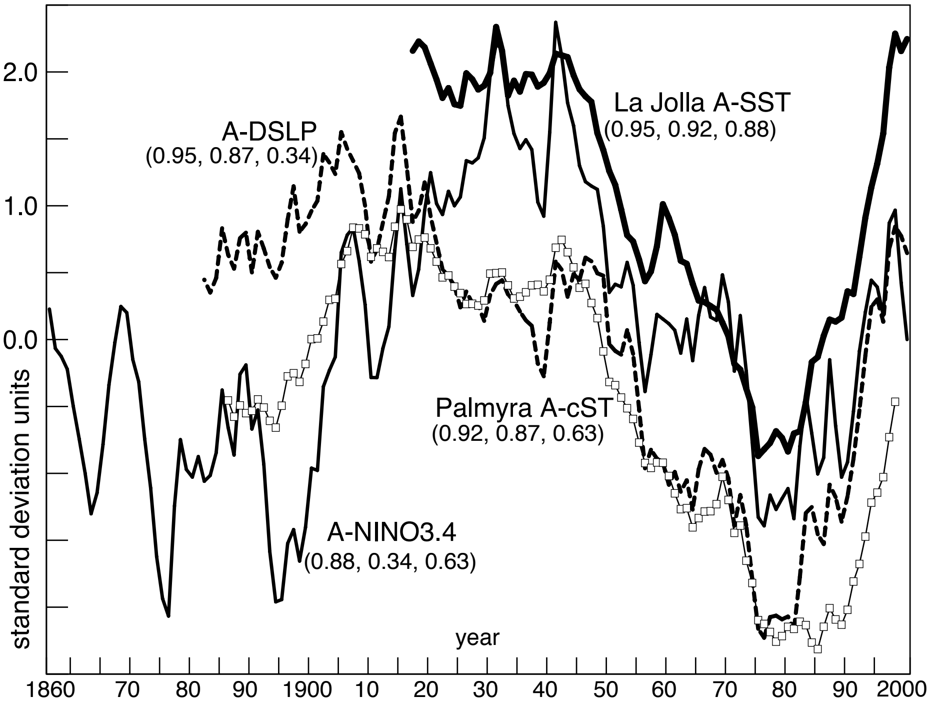

Figure 5. Indices of climate-scale changes from the sea surface temperature for southern California (La Jolla A-SST, heavy, top line); Darwin sea level atmospheric pressure (A-DSLP, broken line); sea temperature derived from coral at Palmyra Island (Palmyra A-cST, open squares); and SST reconstruction for the NINO3.4 equatorial area (A-NINO3.4, lower, solid line). Correlation coefficients appear beneath each series label. From left to right they give coefficients for that series correlated with La Jolla A-SST, A-DSLP, Palmyra A-cST, and A-NINO3.4, excluding the labeled series. All series are standardized and may be offset for clarity. After 1920, the series diverge but show many of the same higher frequency events.

values of the 10-year period. Center-of-the-decade annual values are used throughout the following discussion. Algorithms that allow for temporal errors and find the best fits while allowing temporal error windows will be developed and compared in future reports.

For the 1930–2000 period there is an inverse correlation between sardine and anchovy abundance as measured by the California commercial landings (figs. 2, 4), but the abundance of one species has an orthogonal relationship with the abundance of the other (vertical scale in fig. 2). If Equation 3 is appropriate for the backward extended series, then the orthogonal relationship may cause the anchovy SDR series to be less correlated to the physical indices shown in Figure 5. This will be a test for the particularity or lack of randomness in the two series. When the sardine-scale record is compared to the physical variables for 1920–70, correlations greater the 0.80 are found for all variables (fig. 6). None of the physical variables are strongly related to the anchovy-scale series (not shown). The hypothesis presented by Equation 3 is supported by its relationship to the sardine series and by its lack of relationship to the partially orthogonal anchovy series.

When the 1890–1970 period is considered, A-DSLP and Palmyra A-cST are highly correlated with sardine SDR (0.85 and 0.89, respectively) (fig. 6, second line beneath variable labels). The correlations of these variables with the anchovy-scale SDR increase to 0.58 and 0.20, respectively, but these *r*'-values continue to indicate distinct differences between the sardine and anchovy correlations.

During 1860–1920, the A-NINO3.4 and sardine SDR series are visually similar to those encountered during 1920–70, but the *r*'-values do not reflect these similarities because of accumulated aging inaccuracies in the sardine SDR series (fig. 6). For example, the 1895–1907 period corresponds to the highest sardine SDR in the entire 1860–2000 period and to some of the lowest A-NINO3.4 values. However, the longest period of sustained high-value positive anomalies (sustained, high-value slope) for NINO3.4 corresponds to the high SDR values. Better reconstructions of the NINO3.4 SST anomaly and a more complete development of high temporal resolution, coral-derived sea temperature will likely improve our ability to derive past relationships between sardine abundance in the CFHE and large-scale physical processes. Although the SDR series appears limiting, there is large potential for improving it.

The backward extension of the relationships between sardine abundance and physical variables augments the

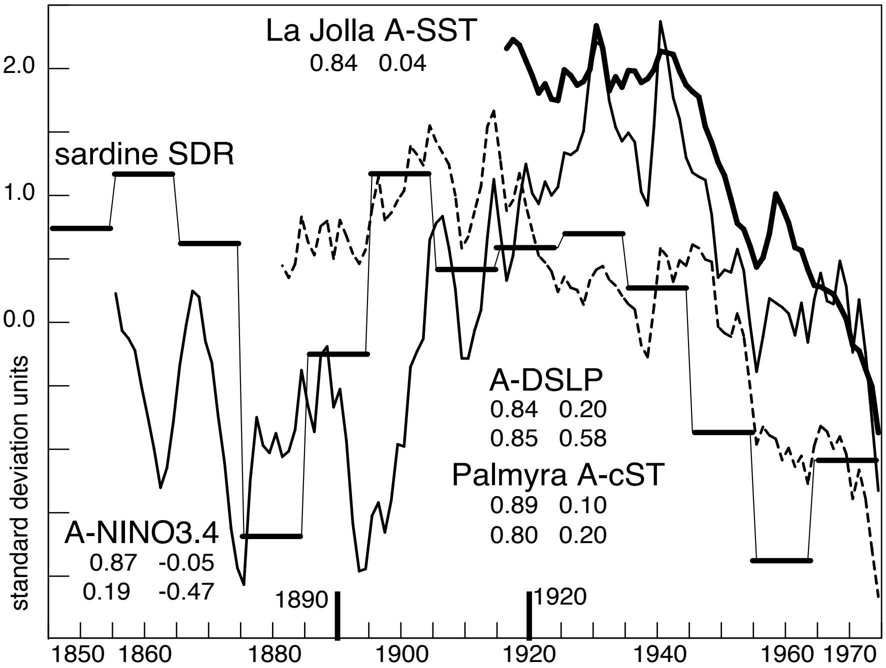

Figure 6. Comparison of decadal average sardine-scale deposition rates (heavy, stepped line) to physical climate variables: accumulated SST anomaly from southern California (La Jolla A-SST, upper, solid line); accumulated sea level atmospheric pressure northern Australia (A-DSLP, broken line), and accumulated SST anomaly in the NINO3.4 area of the equatorial ocean (A-NINO3.4, lower, solid line). The correlation of the scale deposition (SDR) to the physical variables is given below each label, sardine-left and anchovy-right. The anchovy series is not shown. The top two *r*'-values are for the 1920–1970 period and the lower two *r*'-values are for the 1890–1970 period. Because of its similarity to A-DSLP, the accumulated coral sea temperature anomaly (Palmyra A-cST) series is not shown, but its correlations to the sardine and anchovy scale series are shown beneath A-DSLP *r*'-values. All series are standardized and may be offset for clarity.

hypothesis that was formed using sardine landings for the 1930–2000 period (Equation 3); Log_e of sardine abundance is proportional to the time integral of environmental anomalies. The relationship shown in Figure 6 extends the test periods to include 110 years and satisfies conditions of a test independent of the CACom landings series. Extending the series forward to include the 2001–05 period will also provide hypothesis tests, but management and market effects will have to be addressed in this interval. Sardine harvest quotas have been set for each year from 2001 to 2005 by the Pacific Fisheries Management Council, but these quotas have not always been landed. We will discuss this period in future reports.

DISCUSSION

Problems arise when dealing with data from only a few decades when decadal-scale phenomena are investigated. However, three factors suggest that we have found major modes of physical-to-biological interaction: 1) the physical variables suggest relatedness by their similarity to both sardine and C1 variability; 2) the similarity of sardine and C1-s variability suggests that the physical factors affecting sardine abundance also affect the abundance of many other species; and 3) similar results were obtained using SDRs as independent estimates of sardine abundance.

Sardine Abundance and Utilization

Extensive use of CFHE fish and invertebrate resources was promoted by increasing the consumption of fish and fish products locally and by exploitation of world markets by California fish dealers (Wolf et al. 2001; Dietz et al. 2003; Norton and Mason 2004). If the fish population is larger, then the catch will be larger when there is extensive utilization and demand, particularly in unregulated fisheries tied to global markets (Dietz et al. 2003; Norton and Mason 2004). The landings series for sardines appears to be a reasonably good proxy for sardine abundance in the 1930s through the 1950s because of the high exploitation rate of about 40% of sardines 3 years old and older through 1965. Exploitation may have been even higher relative to the low population levels in the 1960s and 1970s (MacCall 1979). The recovery period of the 1980s and 1990s was managed for an exploitation rate of 15% or less (Conser et al. 2004); landings totals are directly proportional to biomass estimates ($r' = 0.97$, for $\log_e$-transformed series) for this period.

In many cases, biomass estimates using available abundance-related indices are better measures of population abundance than California landings, even though biomass estimated for the same time period from multiple indices may vary by 20% or more from one estimation model to another (Conser et al. 2004). However, landings time-series values may change in minor ways as new records are discovered. The record keeping of the California Department of Fish and Game (Mason 2004) has created stable and largely unchanging California sardine landings series that are proportional to state-of-the-art biomass estimates of abundance ($r' = 0.88$, for $\log_e$-transformed series).

When the resource is extensively utilized, economic factors become less important and physical environmental changes contribute more to variability as shown by sardine landings and C1. However, the extent of utilization only affects the present study when landings records are used as indicators of resource abundance (Norton and Mason 2004).

Before the early 1930s, the sardine scale deposition rates (SDR) indicated abundance better than landings because the sardine populations were not extensively utilized. The implication of the relationship between the sardine SDRs and the physical variables (fig. 6) is that the population was larger before and during the development of the industrial fishery in the 1920s than the 1930s and 1940s. It is possible that the continued development of the industrial fishery in the 1930s and 1940s depressed the sardine population to the point of marginal replacement even during these times of good growth and reproduction (sardine SDR, fig.4). When the ocean climate changed in the 1950s, the population reduced rapidly because the sardine population weight responds exponentially to sustained environmental anomalies (Equation 3).

Overall, sardine abundance depends as heavily on the ongoing physical processes, which account for 60–80% of the variability, as any other factor. When 29 species are considered together, physical processes related to C1 and C2 account for about 45% of the overall ensemble variance. Anthropogenic, ecological, and other environmental factors not represented by environmental indices account for more than 50% of the overall variance of the 29 species matrix (see also Norton and Mason 2003, 2005).

A 50–70 year cycle is shown in Figure 2, and similar cycles appear in fisheries and physical variables throughout the northern hemisphere (MacCall 1996; Klyashtorin 2001). Sixty-year cycles are also a dominant mode of temporal variability in the Baumgartner et al. (1992) SDR series. It is likely that much of the California Current ecology is cycling through variable ecosystem composition in 50-to-70-year temporal modes (e.g., fig. 2). If this is the case, then the sardine population biomass may be an indicator of many less conspicuous aspects of the ecosystem.

Ecosystem Management and Prediction

There are two ways that the relationships summarized by Figures 1, 2, 3, and 6 and Equation 3 might be used in management to obtain large yields in favorable growth environments (e.g., 1900–30) and smaller protective yields in unfavorable growth environments (e.g., 1950–75). These are persistence and ecosystem knowledge. From the SDR records of Baumgartner et al. (1992) and present studies, we show that periods of good sardine growth and periods of poor sardine growth are persistent. Management agencies might be especially alert to downturns in sardine production after a few decades of growth and abundance.

Each year there is more ecosystem information to apply to fisheries management. Following the leads of Marr (1960), Jacobson and MacCall (1995), MacCall (1996), and Parrish et al. (2000), we have shown some major physical environmental changes of the CFHE that are associated with high and low sardine production. Persisting anomalies in the environmental indices given herein will be associated with changes in sardine reproduction and recruitment. Current sardine management plans recognize some of these environmental connections, particularly the SST at La Jolla (Conser et al. 2004), but there is ample room for refining management inputs.

There are also predictive possibilities. When sardines are present, favorable environmental conditions are rapidly converted to increased sardine population biomass. The population's increase in weight will then be converted into increases in gametes and possibly recruits. An increase in individuals will depend on the continuing overall adequacy of the environment. Sardine condition and the recruitment-environment indices presented will indicate the continuity within the context of the physical relationships and independent stock assessments. Further investigations into lead-lag relationships among species are likely to show that there are species whose increase or decline regularly precedes sardine abundance changes. Changes in the availability of associated species and strong resurgence of species that do well in conditions different than sardines do (fig. 2, negative EOF1 loading) indicate that ecological changes are occurring. These ecological forewarnings may be used to assess the likelihood of sardine population growth and assist fisheries management decisions.

CONCLUSIONS

The test of the hypothesis that the accumulation of physical process anomalies is directly proportional to an exponential change in sardine abundance (Equation 3) was extended from 71 to 111 years using proxy records of sardine abundance and equatorial measurements of large-scale Pacific processes affecting the California

Current environment. This is a 40-year extension of the sardine abundance time series into the period before the sardine industrial fisheries were developed. The sardine series extension would not have been possible without scale deposition records, since sardine landings weights were relatively small compared to the estimated California Current biomass and may not reflect abundance before 1930. If our results continue to be confirmed, they will allow management decisions based on knowledge of current and probable future fluctuations in sardine and other fishery resources.

There are three related results. First, there are relatively low noise levels in the averaged sardine landings and other landings data. This is shown by the large percentage of variance in sardine landings (60–80%) and in ensemble landings matrices (40–50%) explained by physical variables.

Second, the progression of sardine landings and other species landings maxima appears tied to environmental and ecological conditions that appear to have completed a 50–70 year cycle and returned in the 1990s to physical and biological conditions similar to those of the 1930s and 1940s. Extending the record backward, we note that the conditions of 1980s and 1990s prevailed through the previous high sardine growth and abundance period of late 1800s and early 1900s.

Third, the relationships presented in this report imply that fluctuations in California Current sardine abundance within the 1880–2000 period were as dependent on measurable large-scale physical processes as on anthropogenic factors during all sub-intervals.

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SPAWNING BIOMASS OF PACIFIC SARDINE (*SARDINOPS SAGAX*), FROM 1994–2004 OFF CALIFORNIA

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ABSTRACT

The daily egg production method (DEPM) has been used to estimate the spawning biomass of Pacific sardine (*Sardinops sagax*) since 1986. In this paper, we document the current DEPM procedure using as an example the 2004 survey which incorporates the new procedures adopted since 1997. An adaptive allocation survey design used for sardine eggs has been successfully implemented. Yet, other issues associated with estimating spawning biomass of Pacific sardines remain. We also examine the time series of DEPM spawning biomass estimates and associated parameters from 1994 to 2004 and compare them to the spawning stock biomass (SSB) estimates derived from stock assessment models. The spawning biomass estimates off California increased from less than 10,000 mt in 1986 to 118,000 mt in 1994, to nearly 300,000 mt in 2004 and have fluctuated during the recent years. The spatial distribution of Pacific sardine eggs varied with sea surface temperature. The average fish weight doubled in the last 10 years, as has the reproductive rate.

INTRODUCTION

The spawning biomass of Pacific sardines (*Sardinops sagax*) was estimated independently for 1986[1], 1987[2], 1988[3], 1994 (Lo et al. 1996), and 1996 (Barnes et al. 1997), using the daily egg production method (DEPM: Lasker 1985). Before 1997, Pacific sardine egg production was estimated from direct CalVET[4] (CalCOFI Vertical Egg Tow) (Pairovet) plankton net sampling. Adult fish were sampled in various ways to obtain specimens for batch fecundity, spawning fraction, sex ratio, and average fish weight prior to 1996 (Lo et al. 1996; Macewicz et al. 1996)[1, 2, 3].

As the Pacific sardine population increased, the geographic distribution expanded from inshore to offshore and Pacific sardines reappeared along most of the American continent. The location of spawning biomass and the spatial distributions of Pacific sardine eggs off California vary from year to year[5, 6, 7, 8, 9, 10] partially, perhaps, due to migration (Clark and Jansson 1945). To improve the efficiency of collecting samples of Pacific sardine eggs and larvae, an experimental adaptive allocation sampling design was used in combination with the Continuous Underway Fish Egg Sampler (CUFES; Checkley et al. 1997; Checkley et al. 2000) during the 1996 ichthyoplankton survey (Lo et al. 2001; Smith et al. 2004). Since 1997, in addition to CalVET and Bongo nets, the CUFES has been used as a routine sampler for fish eggs to allocate CalVET samples, and data of sardine eggs collected with CUFES have been incorporated in the estimation procedures of the daily egg production in various ways depending on the survey design (Lo and Macewicz 2004). Since 2001, a cost-effective procedure has been adopted to calculate the DEPM biomass, using

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[4] The diameter of the CalVET net frame is 25 cm; the tow is vertical to minimize the volume of water filtered per unit depth; the mesh size is 0.150 mm, and the depth of tow is 70 m.

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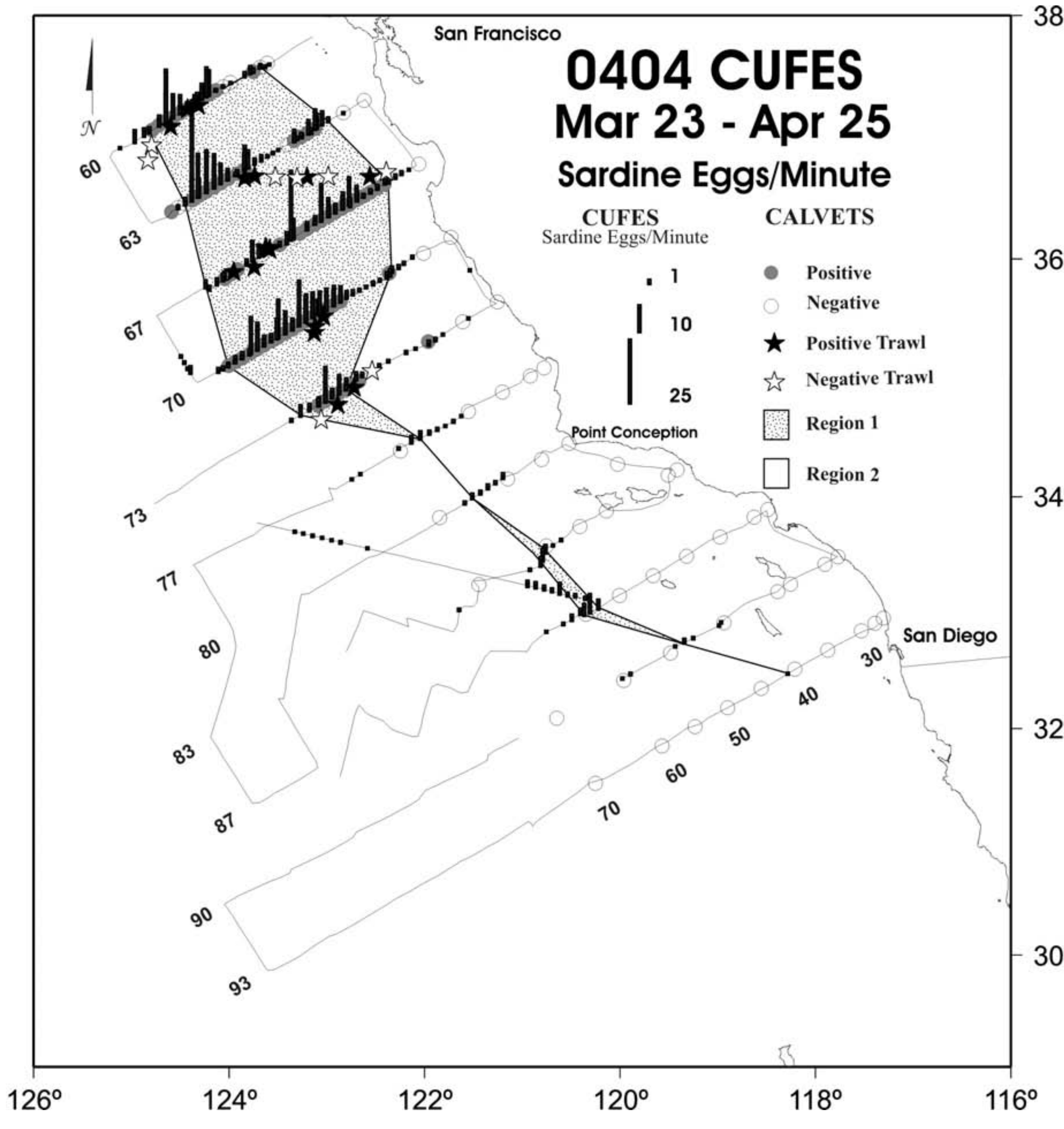

Figure 1. Pacific sardine (*Sardinops sagax*) eggs from the 2004 CalVET (a.k.a. Pairovet) tows and from the 2004 CUFES survey. The numbers on line 93 are CalCOFI station numbers. Trawl survey conducted 21–28 April 2004.

only CalVET samples of eggs and yolk-sac stage larvae in the high-density area (Region 1; fig. 1) defined by the egg density computed from CUFES collections. Data collected from eggs and larvae in Region 1 are used to estimate egg production ($P_{0,1}$) and daily instantaneous embryonic mortality rate in Region 1. The daily egg production in the low density area ($P_{0,2}$) is computed based on $P_{0,1}$ and a correction factor (Lo et al. 2001). The estimate of egg production for the whole survey area is a weighted average of $P_{0,1}$ and $P_{0,2}$.

Although the icthyoplankton survey is conducted yearly, trawl samples were collected only in 1994, 1997, 2001, 2002, and 2004. Except in 1994, sample sizes for trawls were small. For the years 1995–2001, an overall average of the spawning fraction during 1986–94 and estimates of other adult parameters in 1994 were used to estimate daily specific fecundity (number of eggs/gram weight). In 2003, the estimates of adult reproductive parameters from 2002 were used. In 2004, a full-scale survey was conducted to estimate the spawning biomass of Pacific sardine: trawl samples for reproductive output were taken aboard the F/V *Frosti*, and ichthyoplankton samples were taken aboard the R/V *New Horizon* and the NOAA ship *David Starr Jordan*.

The central objective of this paper was to document the current DEPM procedure using as an example the 2004 survey which incorporates the new procedures adopted since 1997. A second objective was to examine the time series of DEPM spawning biomass estimates and associated parameters from 1994 to 2004 and to compare them to the spawning stock biomass (SSB) estimates derived from stock assessment models. The DEPM and the stock assessment models[11] provide quite separate measures of spawning biomass; the former is based on direct measurements, while the latter is inferred from modeled relationships between size and age composition of the catch, maturity, natural mortality, and other factors, such as the DEPM estimate as one of many sets of inputs. Comparisons of these quite separate measures of spawning biomass for years prior to 1995 were examined by Deriso et al. (1996) and are useful because understanding the nature of any differences that may exist could lead to a better understanding of spawning dynamics of Pacific sardine and improved methods for determining them.

MATERIALS AND METHODS

Surveys and Data

Egg Production. CUFES was first used off California in 1996 as an experimental tool to collect eggs of small pelagic fish, like Pacific sardine, northern anchovy (*Engraulis mordax*), and jack mackerel (*Trachurus symmetricus*). It was formally used to collect sardine eggs in 1997. The survey area was post-stratified into high-density and low-density areas according to the egg density from CUFES collections. Staged eggs from CalVET tows and yolk-sac larvae from CalVET and Bongo tows in the high-density area during the April CalCOFI cruise each year were used to model embryonic mortality curve and thus to estimate the daily egg production of sardines in the high-density area[12]. In 1998–2000, eggs from both CalVET and CUFES were staged. Since 2001[7], the CUFES data have been used only to map the spatial distribution of Pacific sardine eggs and to allocate extra CalVET tows in high density areas.

Ichthyoplankton surveys before 1985 and since 2003 have sampled the area from San Diego to San Francisco, and since 2003 two research vessels have been used for the spring ichthyoplankton survey. In 2004, the *New Horizon* conducted the regular CalCOFI survey on CalCOFI lines 93 to 77, whereas the *David Starr Jordan* occupied the area north of line 77 (fig. 1). Bongo samples were taken on all CalCOFI survey lines (fig. 2). For the *David Starr Jordan* portion of the cruise, CalVET tows were taken at 4 nm intervals on each line whenever the egg density from each of two consecutive CUFES samples exceeded 1 egg/min, the threshold value, and were stopped when the egg density from each of two consecutive CUFES samples was <1 egg/min. The threshold value was reduced to 1 egg/min from 2 used in years prior to 2002 to increase the size of the high density area and the number of CalVET samples. This adaptive allocation sampling, similar to the 1997 survey (Lo et al. 2001; Smith et al. 2004), was used only aboard *David Starr Jordan*. The number of positive samples for eggs and larvae collected by CalVET and CUFES is quite different between Regions 1 and 2, as expected (tab. 1).

Prior to 2001, eggs collected from both CalVET and CUFES were used to model embryonic mortality. Because CUFES samples at a fixed 3 m water depth, a catch ratio (E), eggs/min = E eggs/0.05 m^2, was calculated to convert abundance of eggs from CUFES to the full water column. Egg densities from each CalVET sample and the CUFES samples taken within an hour before and an hour after the CalVET tows (a total of a two hour interval) were paired. We used a regression estimator to compute the ratio of mean eggs/min from CUFES to mean eggs/tow from CalVET, $E = U_y/U_x$, where y is the eggs/min and x is eggs/tow (Lo et al. 2001). Even though this conversion factor was no longer needed after 2000, it is informative in regard to water mixing and behavior of the spawning population.

Spatial Distribution of Sardine Eggs with Sea Surface Temperature. The CUFES collections of pelagic fish eggs are continuous and can be used to examine their spatial distribution together with oceanographic and biological data (Lynn 2002). For surveys conducted on the NOAA ships *David Starr Jordan* (1996–2004) and *McArthur* (2002), sea surface temperature and salinity were measured continuously at a depth of 2 m with a SBE-21 thermosalinograph (TSG) mounted inside a sea chest in the ships' hulls. Data from the TSG were sent to the ship's scientific computer system (SCS) which provided temperature and salinity values and GPS location related to each CUFES sample to the CUFES software. For samples collected on the R/V *New Horizon* (2004) and R/V *Roger Revelle* (2003), temperature and salinity were measured with a SBE-45 micro TSG using seawater drawn by the CUFES at a depth of 3 m. Data with GPS software were sent to a portable SCS to be stored and distributed to the CUFES software.

Data collected by the CUFES software were mapped to show relative abundance of pelagic eggs over temper-

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[11] Conser, R., K. Hill, P. Cone, N. C. H. Lo, and R. Felix-Uraga. 2004. Assessment of the Pacific sardine stock for U.S. management in 2005. Submitted to Pacific Fishery Management Council. Portland, OR. http://swfsc.nmfs.noaa.gov/frd/Coastal%20Pelagics/Sardine/Sardine_Assessment_Nov_2004_revised.pdf

[12] Hill, K. T., L. D. Jacobson, N. C. H. Lo, M. Yaremko, and M. Dege. 1999. Stock assessment of Pacific sardine for 1998 with management recommendations for 1999. Admin. Rep. 99-4. Marine Region, California Department of Fish and Game.

TABLE 1
Number of Positive Tows of Sardine Eggs (*Sardinops sagax*) from CalVET, Yolk-sac Larvae from CalVET and Bongo, and Eggs from CUFES in Region 1 (eggs/min ≥1) and Region 2 (eggs/min <1) for Both *New Horizon* (NH) and *David Starr Jordan* (Jord) Cruises 0404

		Region						Total	NH	Jord
		1			2					
		Total	NH	Jord	Total	NH	Jord			
CalVET eggs	positive	63	0	63	4	0	4	67	0	67
	Total	71	1	70	53	40	13	124	41	83
CalVET yolk-sac	positive	46	0	46	4	1	3	50	1	49
	Total	71	1	70	53	40	13	124	41	83
Bongo yolk-sac	positive	9	0	9	22	15	7	31	15	16
	Total	11	1	10	75	60	15	86	61	25
CUFES eggs	positive	164	10	154	87	29	58	251	39	212
	Total	181	10	171	600	422	178	781	432	349

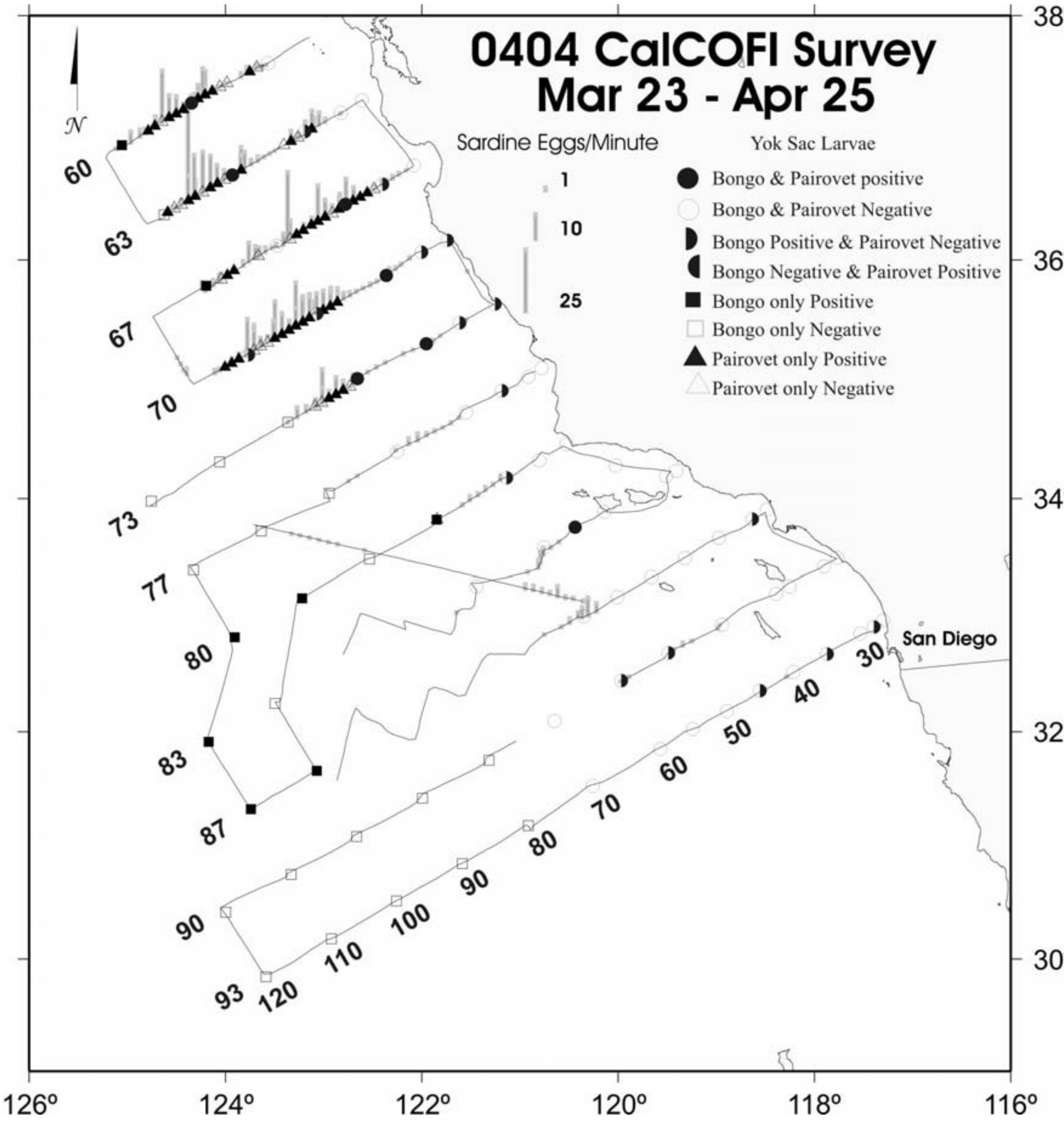

Figure 2. Sardine (*Sardinops sagax*) yolk-sac larvae from CalVET (a.k.a. Pairovet; circle and triangle) and from Bongo (circle and square) in the 2004 surveys.

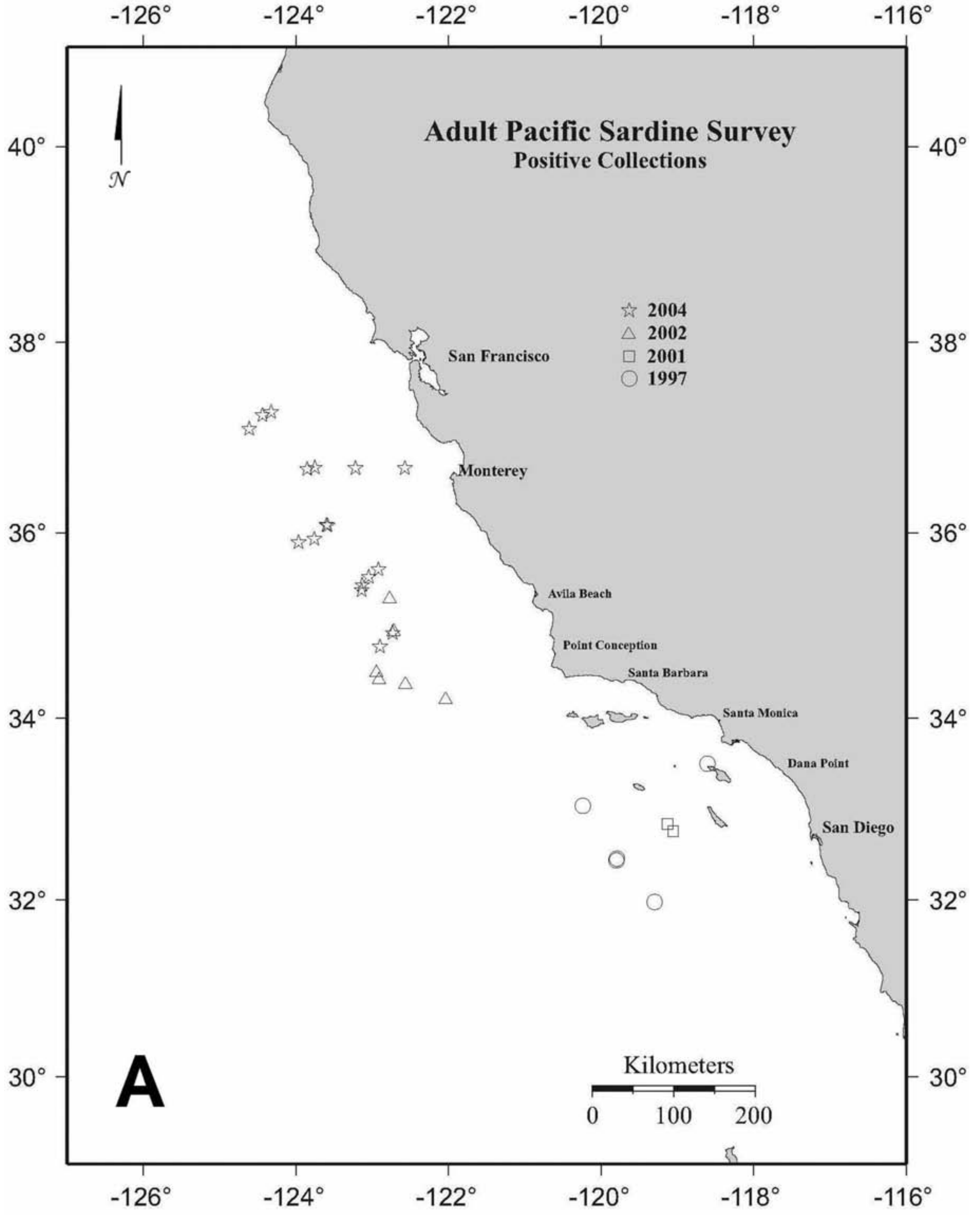

Figure 3A. Locations of adult Pacific sardine (*Sardinops sagax*) samples. A - adults taken by trawls.

ature contours. These contours were created with General Mapping Tools software using a blockmedian transformation for arbitrarily located x, y, and z values and smoothed using a surface tension adjustment (Smith and Wessel 1990).

Adult Pacific Sardine Sampling. Adult Pacific sardines were collected from San Diego to as far north as San Francisco during 1997, 2001, 2002, and 2004 (fig. 3). During 1997–2002, samples were taken aboard the NOAA ship *David Starr Jordan* using a high-speed mid-

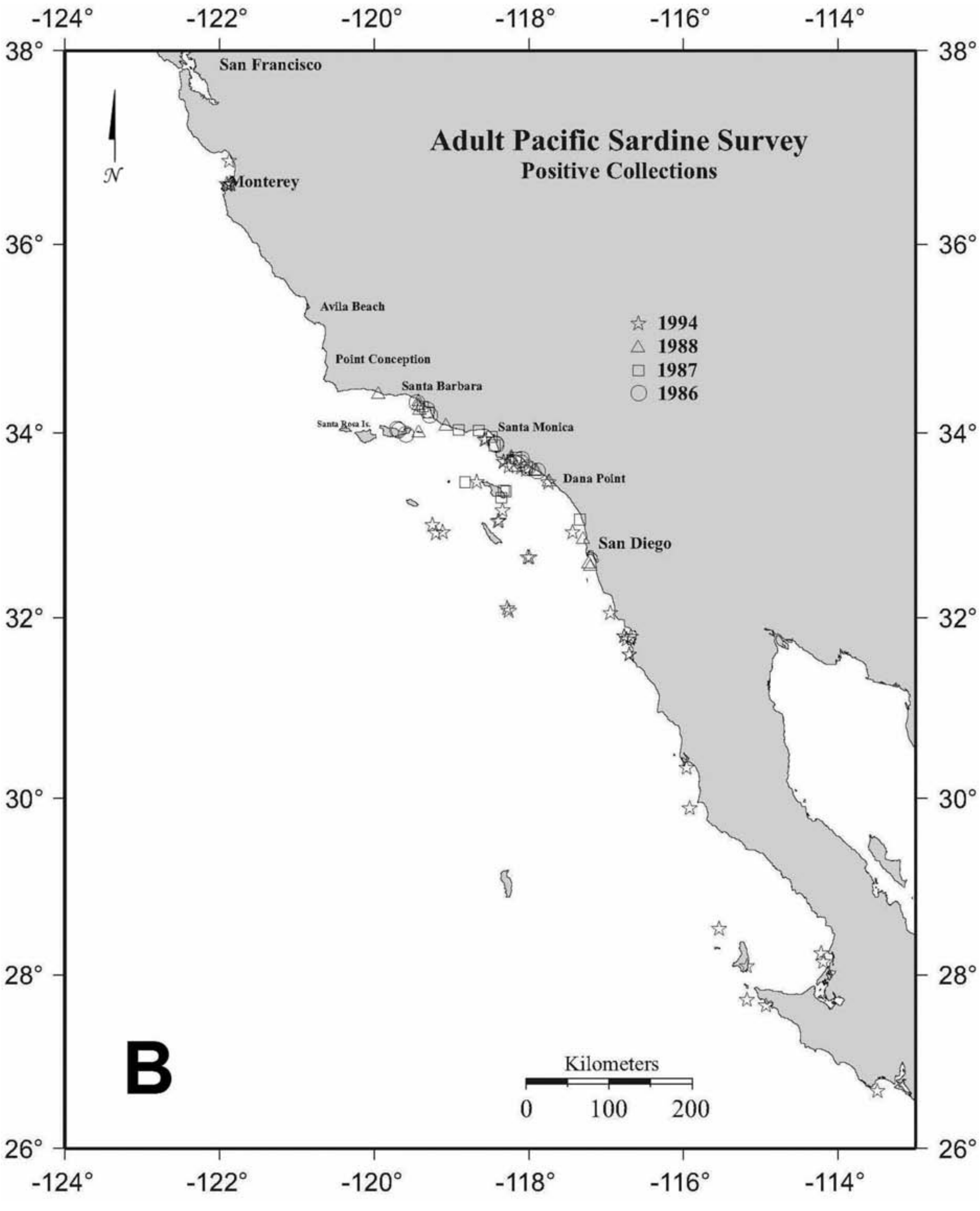

Figure 3B. Locations of adult Pacific sardine (*Sardinops sagax*) samples. B - adults taken by trawls and purse seines (1994) or only purse seines (1986–88).

water trawl, while in 2004 sardine samples were collected aboard the F/V *Frosti* using a Nordic 264 midwater trawl. Allocation of trawls was based on evidence of schools on echosounder or sardine eggs in CUFES samples. Collections of sardines were taken at night between 2017 and 0431 hours (tab. 2). Up to 50 fish randomly sampled from each collection were sexed and standard length was measured to the nearest millimeter. All fish sampled were individually weighed to the nearest gram, except in 1997 when the first 25 fish and all

TABLE 2
Proportion of Female Pacific Sardine (*Sardinops sagax*) by Weight[a] Taken in Trawls, and Collection Information during 1997, 2001, 2002, and 2004

Year	Month	Day	Time (h m)	Collection number	Latitude °N	Longitude °W	Surface temp. °C	Headrope depth	Random sample size	Proportion of females
1997	4	6	313	1809	33.5062	118.6067	15.8	25	18	0.281
	3	16	2121	1805	33.0407	120.2433	13.4	15	10	0.391
	4	3	2205	1807	32.4522	119.7933	13.8	20	50	0.618
	4	4	236	1808	32.4398	119.7983	13.7	37	50	0.396
	3	12	2021	1804	31.9723	119.2967	14.7	17	50	0.754
2001	5	2	340	5004	32.8393	119.1287	13.1	15	5	0.690
	5	1	2347	5003	32.7621	119.0579	12.8	25	11	0.670
2002	4	23	2017	5016	35.2867	122.7767	12.7	30	1	1.000
	4	21	2108	5010	34.9400	122.7183	12.5	30	2	0.472
	4	22	216	5011	34.4950	122.9500	13.0	31	14	0.458
	4	22	355	5012	34.4200	122.9133	13.3	31	7	0.565
	4	18	146	5006	34.3683	122.5700	12.6	25	12	0.096
	4	21	431	5009	34.2017	122.0417	12.6	30	25	0.399
2004	4	22	109	2111	37.2700	124.3280	13.3	0	50	0.565
	4	27	2049	2132	37.2402	124.4380	13.5	0	1	0.000
	4	27	2359	2133	37.0968	124.6120	14.0	0	10	0.621
	4	23	2248	2118	36.6876	123.7520	13.4	0	3	0.741
	4	22	2221	2113	36.6828	122.5750	12.3	0	1	1.000
	4	23	414	2115	36.6802	123.2190	13.1	0	50	0.611
	4	24	25	2119	36.6740	123.8550	13.6	0	3	1.000
	4	26	2049	2128	36.0815	123.5990	13.8	0	50	0.827
	4	26	2253	2129	36.0730	123.5890	13.8	20	50	0.536
	4	27	124	2130	35.9343	123.7570	13.6	0	50	0.813
	4	27	353	2131	35.8958	123.9650	13.6	0	50	0.351
	4	24	2046	2120	35.6080	122.9200	13.7	0	7	0.745
	4	24	2250	2121	35.5260	123.0460	13.8	0	49	0.560
	4	25	130	2122	35.4382	123.1310	13.8	0	50	0.512
	4	25	330	2123	35.3840	123.1400	13.7	0	50	0.725
	4	25	2311	2125	34.9271	122.7340	14.1	0	50	0.618
	4	26	140	2126	34.7815	122.9020	13.9	0	50	0.599

[a] Sex ratio based on average weights (Picquelle and Stauffer 1985).

females in each sample were individually weighed. Otoliths were removed for aging and gonads were removed and preserved in 10% neutral buffered formalin. After the random subsample, additional fish were processed following procedures used in 1994 (Macewicz et al. 1996).

In the laboratory, each preserved ovary was processed (Hunter and Macewicz 1985). We analyzed oocyte development, atresia, and postovulatory follicle age to assign female maturity and reproductive state (Macewicz et al. 1996). Immature females were defined as those having ovaries with no β atresia and only unyolked oocytes present (a few oocytes may be in the earliest stage of yolk deposition). Some immature ovaries may contain α atresia of unyolked oocytes. Mature females were classified as active or postbreeding. Active, mature females are capable of spawning and are identified as having ovaries containing oocytes with yolk or postovulatory follicles less than 60 hours old. Postbreeding females are considered incapable of further spawning in the season and are identified by the presence of β atresia in ovaries with only unyolked oocytes and without postovulatory follicles (Macewicz et al. 1996). Sufficient numbers of immature and mature females for estimating the length at which 50% were mature were collected only during 2004. Females from 2004 were grouped into 10 mm length classes, and the length at which 50% were mature was estimated by logistic regression.

Daily Egg Production (P_0)

Since 2001, we have used the net tow instead of the transect line as the sampling unit (Lo et al. 2001)[7] because eggs from CUFES are not used to model the embryonic mortality curve. Eggs classified into developmental stages from CalVET tows and yolk-sac larvae from both CalVET and Bongo tows in Region 1 were used to compute egg production (figs. 1 and 4). The modeling procedures were modified from Lo et al. (2001). We used individual egg counts at age, and not half-day age groups, as input to fit an exponential embryonic mortality curve for the high-density area using a weighted nonlinear regression (Picquelle and Stauffer 1985; Lo et al. 1996).

The final estimate of $P_{0,1}$ was corrected for a bias introduced from the nonlinear regression. A simulation

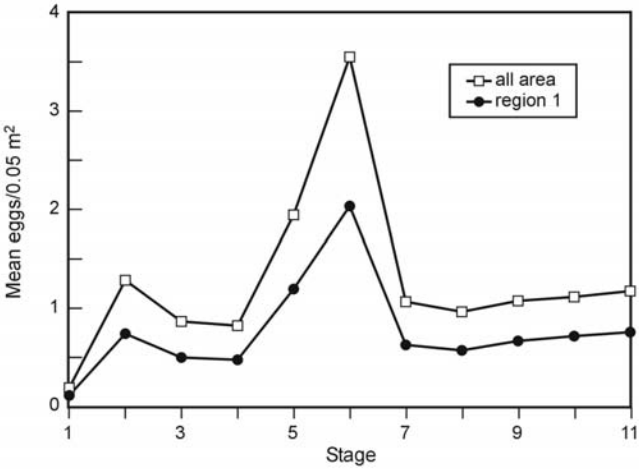

Figure 4. Pacific sardine (*Sardinops sagax*) eggs/0.05 m² for each developmental stage from March–April 2004.

study[7] indicated that $P_{0,1}$ computed from a weighted nonlinear regression based on the original data points has a relative bias (RB) of –0.04 of the estimate where RB = (mean of 1,000 estimates – true value)/mean of 1,000 estimates. Therefore, the bias-corrected estimate is $P_{0,1,c} = P_{0,1} * (1 - \text{RB}) = P_{0,1} * 1.04$, and $\text{SE}(P_{0,1,c}) = \text{SE}(P_{0,1}) * 1.04$. The daily egg production in the low-density area ($P_{0,2}$) is $P_{0,1,c} * q$; where q is the ratio of eggs/min in the low-density area to that of the high-density area based on CUFES data. The estimate of egg production for the whole survey area is a weighted average of $P_{0,1}$ and $P_{0,2}$ where the weight is the area size of each region (Lo et al. 2001).

Adult Parameters

We followed methods in Macewicz et al. (1996) to evaluate the adult parameters (Picquelle and Stauffer 1985): fraction of the population by weight that is female (weight-specific sex ratio, R); average weight of mature females (W_f); number of oocytes released per spawn (batch fecundity, F); and daily spawning rate of mature females (spawning fraction, S). Two minor variations in the methods were necessary. First, for the daily spawning fraction in 2002, the number of spawning females per trawl (the numerator) was computed as an average of the number of females spawning two nights before capture and those spawning the night after capture[8, 10, 13]. Secondly, since females necessary for determining the relationship between batch fecundity and ovary-free female weight (W_{of}) were scarce before 2004 (two in 2002), we used the regression equation from 1994 (Macewicz et al. 1996) to estimate F, while in 2004 we used the relationship from 39 females collected that year. We compared the 2004 results with batch fecundity data from 1986–1994 (Macewicz et al. 1996)[1]. The basic formulas for the population mean and variance for the adult reproductive parameters are in Picquelle and Stauffer (1985) and Lo et al. (1996).

Spawning biomass (B_s)

The spawning biomass was computed according to:

$$B_S = \frac{P_0 AC}{RSF/W_f} \qquad (1)$$

where A is the survey area in units of 0.05 m², C is the conversion factor from gm to mt, P_0A is the total daily egg production in the survey area, and the denominator (RSF/W_f) is the daily specific fecundity (number of eggs/population weight (g)/day).

The variance of the spawning biomass estimate ($\hat{B}_s$) was computed from the Taylor expansion as a function of the coefficient of variation (CV) of the estimate for each parameter and the covariance for adult parameter estimates (Parker 1985):

$$VAR(\hat{B}_s) = \hat{B}_s^{\,2}[CV(\hat{P}_0)^2 + CV(\hat{W}_f)^2 + CV(\hat{S})^2 + CV(\hat{R})^2 + CV(\hat{F})^2 + 2COVS] \qquad (2)$$

The covariance term is:

$$COVS = \sum_i \sum_{i<j} \text{sign} \frac{COV(x_i, x_j)}{x_i x_j}$$

where x's are the adult parameter estimates, and subscripts i and j represent different adult parameters; e.g., $x_i = F$ and $x_j = W_f$. The sign is positive if both parameters are in the numerator or denominator of B_S (equation 1); otherwise, the sign is negative.

When the estimates of adult reproductive parameters are not available, $CV^2(\hat{B}_s) = var(\hat{B}_s)/(\hat{B}_s)^2$ (equation 2) could be approximated by $CV(\hat{P}_0)^2 + allCVsCOV$ where the equation $allCVsCOV = CV(\hat{W})^2 + CV(\hat{S})^2 + CV(\hat{R})^2 + CV(\hat{F})^2 + 2COVS$ is computed from data collected during the previous trawl survey[9].

Spawning Stock Biomass from the Stock Assessment Model

The recent stock assessment model used for Pacific sardine is the Age-Structure Assessment Program (ASAP) model (Legault and Restrepo 1998)[11]. This model uses a general estimation approach, which is a flexible forward-simulation that allows for the efficient and reliable estimation of a large number of parameters. For Pacific sardine, a number of fishery-independent spawning biomass-related time series was used as indices in the model, among which is the time series of the annual estimates

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[13] Chen, H., N. Lo, and B. Macewicz. 2003. MS ACCESS programs for processing data from adult samples, estimating 86 adult parameters and spawning biomass using daily egg production method (DEPM). Admin. Rep. LJ-03-14. Southwest Fisheries Science Center, National Marine Fisheries Service. La Jolla, CA.

from DEPM from 1983–2004. The predicted spawning stock biomass (SSB) was calculated basically following that of Deriso et al. (1996):

$$\hat{I}_{DEPM} = q\hat{SSB}$$

where I_{DEPM}, the DEPM spawning biomass index, and q, a scaling parameter, were estimated from the model. The index was taken to represent sardine SSB. The modeled selectivity pattern was set using the proportion of sardines mature at age (tab. 9 in Conser[11]). For the time series of spawning stock biomass, while the historical data (1932–1965) were not formally used in the model, the historical VPA biomass estimates derived from them were qualitatively used to establish the scale of virgin SSB in the ASAP modeling of the contemporary period.

RESULTS

Eggs

Egg Production (P_0). The embryonic mortality curve of egg production of Pacific sardine (*Sardinops sagax*) off California from San Diego to San Francisco in 2004 included $P_{0,1}$ = 3.78/0.05 m² (CV = 0.23) and the instantaneous daily mortality rate z = 0.25 (CV = 0.04) for Region 1 (fig. 5). $P_{0,1,c}$ after correction for bias was 3.92/0.05 m² (CV = 0.23). The egg production for Region 2, $P_{0,2}$ was 0.16/0.05 m² (CV = 0.43), and the egg production for the entire survey area was 0.96/0.05 m² (CV = 0.24) in 2004. The egg production increased from 0.193/0.05 m² (CV = 0.22) in 1994 to close to 1/0.05 m² (CV = 0.24) in 2004, with the peak of 4.23 eggs/0.05 m² (CV = 0.4) in 2000 (tab. 3). Daily embryonic mortality rates ranged from 0.10 (CV = 0.6) in 1999 to 0.48 (CV = 0.08) in 2003 (tab. 3).

Catch Ratio between CUFES and CalVET (E). In 2004, the catch ratio of eggs/min to eggs/tow (E) computed from 66 pairs of CalVET tows and CUFES collections (excluding a tow with 200 eggs, as the maximum in all other tows was <50) was 0.22 (CV = 0.09) (fig. 6). A ratio of 0.22 means that one egg/tow from CalVET tow is equivalent to approximately 0.22 egg/min from a CUFES sample, or one egg/minute from the CUFES is equivalent to 4.54 eggs/tow from a CalVET sample. Although this ratio is no longer needed in the estimation procedure, we compute it for comparison purposes every year (see discussion).

Spatial Distribution of Sardine Eggs and Sea Surface Temperature

The spatial distribution of spawning for Pacific sardines in relation to temperature contours from 1996–2004 appears to follow some general trends (figs. 7–9). Pacific sardines spawned within the temperature range of 12°C to 14°C, with occasional spawning activity at 15°C. The spawning regions tended to shift to the north over the years. Pacific sardines spawned closer to the shore in years with high temperature, e.g. in 1998. However, when the average temperature was low (in 1999 and 2001), the spawning was more offshore (tab. 3; figs 7–9). The egg distributions of northern anchovy and jack mackerel were included in Figures 7–9 for comparison purposes.

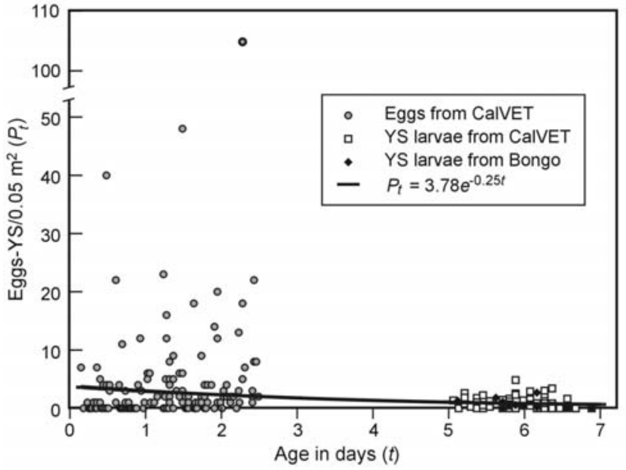

Figure 5. Pacific sardine (*Sardinops sagax*) embryonic mortality curve for eggs and larvae during March–April survey in 2004. The number, 3.78, is the estimate of daily egg production before correction for bias.

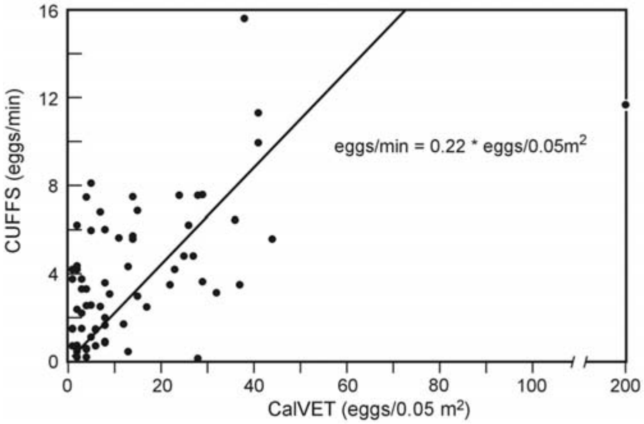

Figure 6. The catch ratio (0.22) of Pacific sardine (*Sardinops sagax*) egg density from paired CUFES and CalVET samples in 2004 (n = 66, p<0.01).

Adult Parameters

The average whole wet weight of mature females, adjusted for bias (tab. 4), ranged from 75.58 to 228 g, and ovary-free wet weight ranged from 71.69 to 216.13 g (tab. 5). The estimates of W_f and W_{of} were highest in the 2004 survey (tab. 6). The ranges in standard length (SL) are fairly similar despite small sample sizes in 2001 and 2002 (tab. 6). A logistic regression indicated that fifty percent of females in 2004 were sexually mature at 193.34 mm SL (fig. 10).

TABLE 3
Estimates of Pacific Sardine Daily Egg Production (P_0)[a] for the Survey Area, Daily Instantaneous Mortality Rates (*Z*) from High Density Area (Region 1), Daily Specific Fecundity (*RSF/W*), Spawning Biomass of Pacific Sardine (*Sardinops sagax*), and Average Sea Surface Temperature for the Years 1994 to 2004

Year	P_0 (CV)	Z (CV)	Area (km^2) (Region 1)	$\frac{RSF}{W}$	Spawning biomass (mt) (CV)[b]	Ave. temperature for positive egg or yolk-sac samples (°C)	Mean temperature (°C)
1994	0.193[c] (0.22)	0.120 (0.97)	380,175 (174,880)	11.52	127,102 (0.32)	14.3	14.7
1995	0.830 (0.5)	0.400 (0.4)	113,188.9 (113,188.9)	23.55[d]	79,997 (0.6)	15.5	14.7
1996	0.415 (0.42)	0.105 (4.15)	235,960 (112,322)	23.55	83,176 (0.48)	14.5	15.0
1997	2.770 (0.21)	0.350 (0.14)	174,096 (66,841)	23.55[e]	409,579[e] (0.31)	13.7	13.9
1998	2.279 (0.34)	0.255 (0.37)	162,253 (162,253)	23.55	313,986 (0.41)	14.38	14.6
1999	1.092 (0.35)	0.100 (0.6)	304,191 (130,890)	23.55	282,248 (0.42)	12.5	12.6
2000	4.235 (0.4)	0.420 (0.73)	295,759 (57,525)	23.55	1,063,837 (0.67)	14.1	14.4
2001	2.898 (0.39)	0.370 (0.21)	321,386 (70,148)	23.55	790,925 (0.45)	13.3	13.2
2002	0.728 (0.17)	0.400 (0.15)	325,082 (88,403)	22.94	206,333 (0.35)	13.6	13.6
2003	1.520 (0.18)	0.480 (0.08)	365,906 (82,578)	22.94	485,121 (0.36)	13.7	13.8
2004	0.960 (.24)	0.250 (0.04)	320,620 (68,234)	21.86[f]	281,639[f] (0.31)	13.4	13.7

[a] weighted non-linear regression on original data and bias correction of 1.04, except in 1994 and 1997 when grouped data and a correction of 1.14 was used (appendix Lo 2001).

[b] $CV(B_s) = (CV^2(P_0) + allCVsCOV)^{1/2} = (CV^2(P_0) + 0.054)^{1/2}$. For 1995–2001 allCVsCOV was from 1994 data (Lo et al. 1996). For 2003, allCVsCOV was from 2002 data (Lo and Macewicz 2002).

[c] bias correction (1.14; appendix Lo 2001) of original result (0.169; Lo et al. 1996).

[d] 23.55 was from computation for 1994 based on $S = 0.149$ (the average spawning fraction (day 0 and day 1) of active females from 1986–1994; Macewicz et al. 1996).

[e] is 25.94 when calculated from parameters in table 6 and estimated spawning biomass is 371,725 with CV = 0.36.

[f] uses R = 0.5 (Lo and Macewicz 2004); if using actual R = 0.618, then value is 27.0 and biomass is estimated as 227,746.

The relationship between female weight (without ovary, W_{of}) and batch fecundity (F_b) in the 2004 was $F_b = 356.46W_{of}$ ($n = 39$)[10]. This equation was used to estimate batch fecundity for each of the 290 mature females in 2004, and the estimated mean batch fecundity was 55,711 (tab. 6). For estimates of mean batch fecundities in 1997, 2001, and 2002, we used the 1994 fecundity equation ($F_b = -10585 + 439.53W_{of}$), with 1994 data for comparison purposes (tab. 6).

We used analysis of covariance to test the differences in the relationship between batch fecundity and female weight (W_{of}) among 1986, 1987, 1994, and 2004 (fig. 11). We included data from fish between 69 and 200 g because this range encompassed data from each of the four years. The difference among slopes from the four data sets was barely significant ($p = 0.058$). Assuming the slopes were equal, covariance analysis indicated that the adjusted group means were not different at the 10% significant level ($F_{3,\,158} = 2.55$, $p = 0.097$). Combining the data from all five years yielded the equation: $F_b = -12042 + 452.69W_{of}$, where $n = 190$, $r^2 = 0.799$ and W_{of} ranged from 39 to 244 grams (fig. 11).

TABLE 4
Relation of Wet Weight (*W*) and Ovary-free Wet Weight (W_{of}) for Non-hydrated Female Pacific Sardine (*Sardinops sagax*) for 1997, 2002, and 2004

	Linear equation $W = a + bW_{of}$					
Year	a	b	r^2	F	N	Range of W in grams
1997	0	1.069		182143	107	82–191
2002	0	1.088		20480	17	120–197
2004	–4.24	1.094	0.989	30303	324	31–261

The average fraction of mature female sardine spawning per day, when the estimate was based on females spawning on the night of capture, was 0.133 in 1997 and 0.131 in 2004 (tab. 6). No female in 2002 was identified as spawning on the night of capture (tab 5); the estimate in that year was 0.174 mature females spawning per day (Lo and Macewicz 2002).

Spawning Biomass

The spawning biomass in 2004 was estimated to be 281,639.27 mt ($CV = 0.3$) for an area of 320,619.8 km^2,

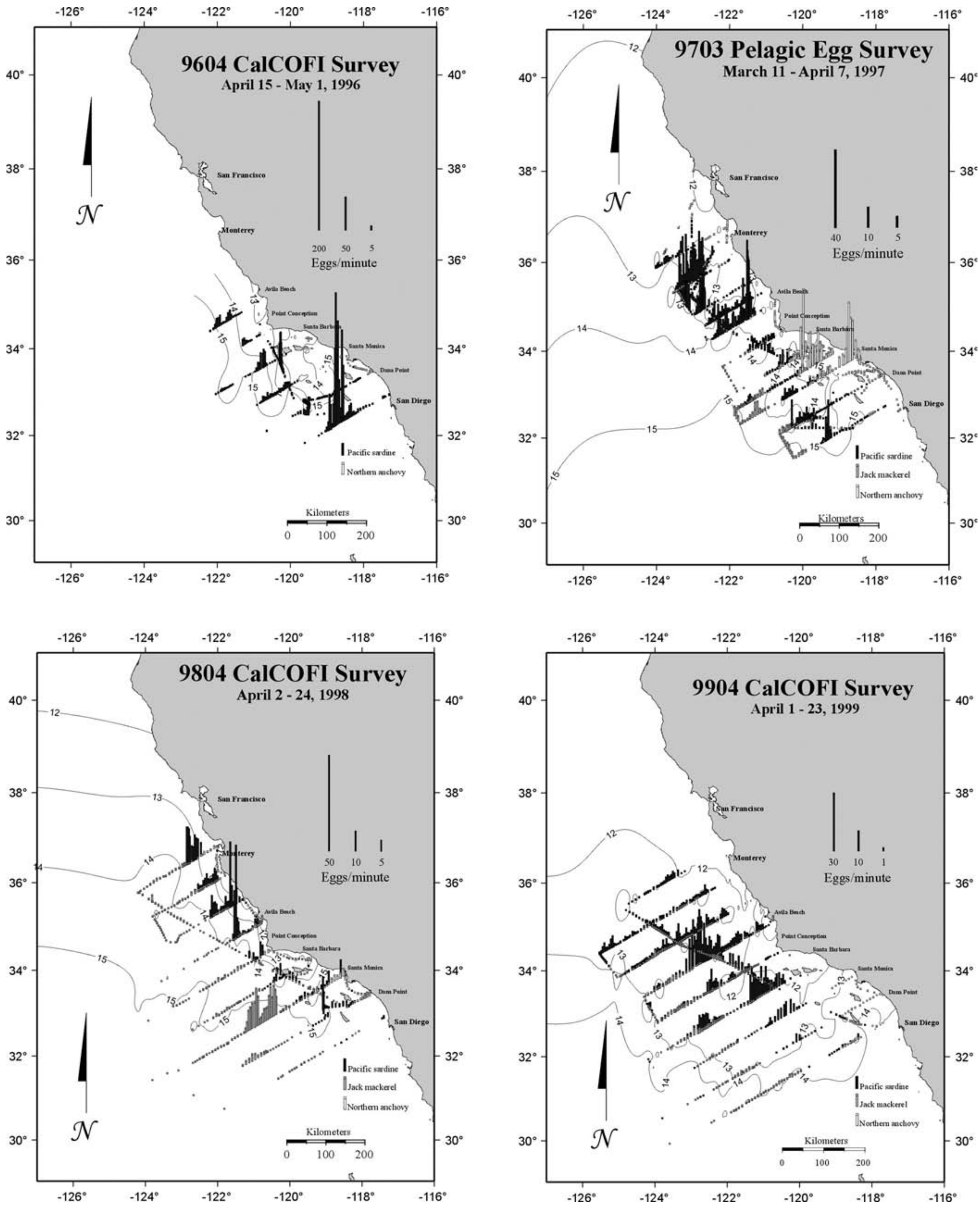

Figure 7. Eggs/minute of Pacific sardine (*Sardinops sagax*), jack mackerel (*Trachurus symmetricus*) and Northern anchovy (*Engraulis mordax*) and sea surface temperature isotherms from 1996–99.

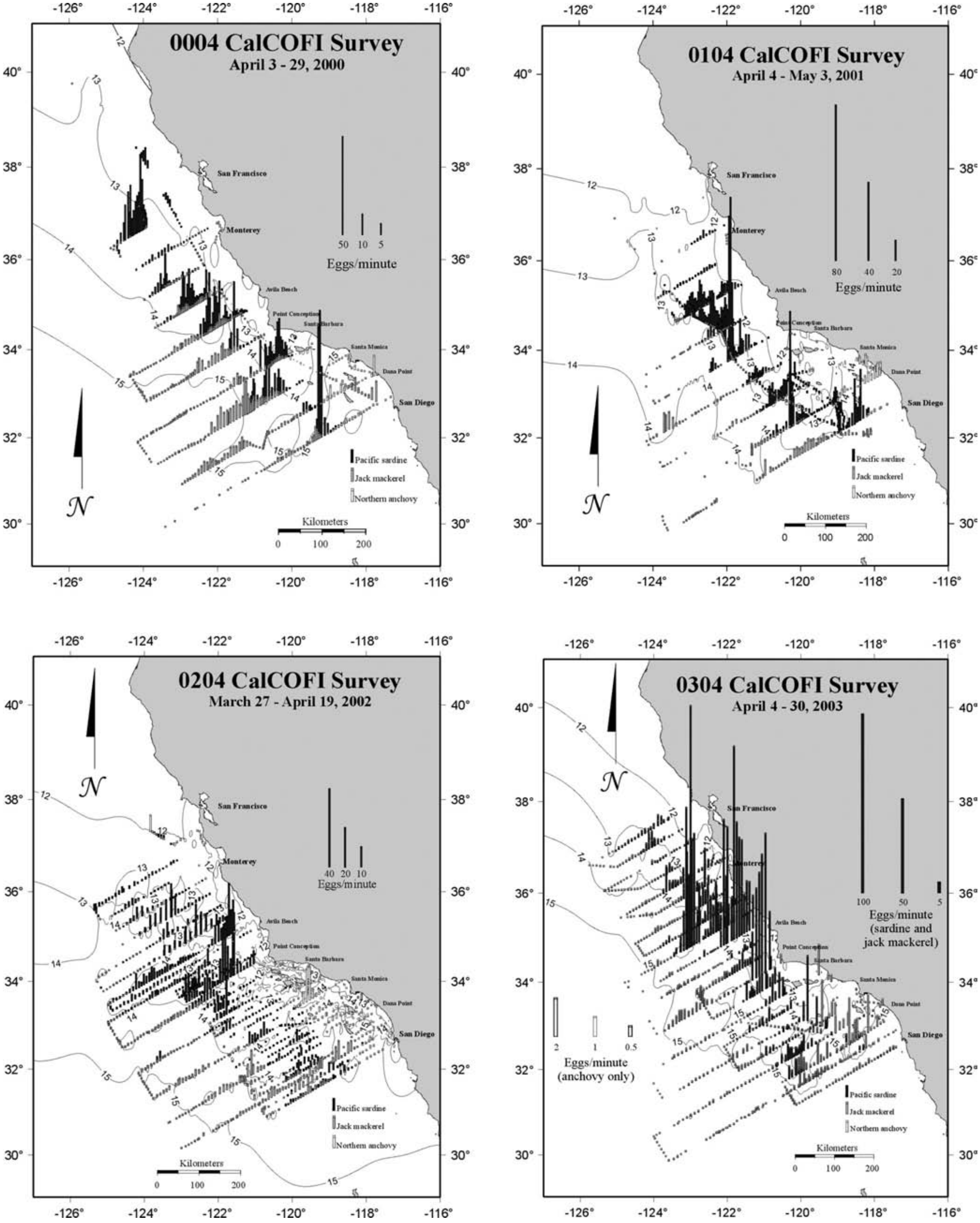

Figure 8. Eggs/minute of Pacific sardines (*Sardinops sagax*), jack mackerel (*Trachurus symmetricus*) and Northern anchovy (*Engraulis mordax*) and sea surface temperature isotherms from 2000–03.

TABLE 5
Parameters for Mature Female Pacific Sardine (*Sardinops sagax*) Used in Estimation of Biomass from Individual Samples

					Number of females spawning				Spawning fraction		
Year and collection number	Number	Average wet weight (g)	Average ovary-free weight (g)	Average batch fecundity	Night of capture	Night before capture	Two nights before capture	No spawn within last 60 hours	Night of capture "Day 0"	Night before capture "Day 1"[a]	Number of mature females adjusted[b]
1997											
1809	5	104.20	na	na	na	na	na	na	na	na	na
1805	3	95.51	88.51	28317	1	0	0	2	0.333	0.000	2
1807	25	132.40	124.92	44319	3	3	3	16	0.120	0.120	25
1808	24	115.58	108.66	37174	8	6	2	8	0.333	0.273	22
1804	25	138.68	128.66	45964	0	1	7	17	0.000	0.038	26
all	77				12	10	12	43			75
2001											
5004	3	86.07	82.15	25520	0	0	0	3	0	0	3
5003	6	75.58	71.69	20923	1	0	0	5	0.167	0	6
all	9				1	0	0	8			9
2002											
5016	1	178.74	178.74	53721	1	0	0	0	1.000	0.000	1
5010	1	142.37	142.37	42811	1	0	0	0	1.000	0.000	1
5011	6	170.83	159.43	47930	2	0	3	1	0.333	0.025	6
5012	4	147.00	136.42	41026	2	0	0	2[c]	0.500	0.025	4
5006	1	188.00	163.91	49274	0	0	0	1[c]	0.000	0.500	1
5009	10	149.73	141.34	42503	6	0	2	2	0.600	0.100	10
all	23				12	0	5	6			23
2004											
2111	25	178.72	167.80	59815	2	3	3	17	0.080	0.115	26
2132	0	0.00	0.00	0	0	0	0	0	0.000	0.000	0
2133	6	178.05	167.65	59761	4	1	0	1	0.667	0.333	3
2118	2	180.71	169.11	60282	1	0	0	1	0.500	0.000	1
2113	1	228.00	216.13	77041	0	0	0	1	0.000	0.000	1
2115	25	176.48	165.97	59160	2	1	3	19	0.080	0.042	24
2119	3	201.67	189.17	67430	0	2	0	1	0.000	0.400	5
2128	25	148.88	140.19	49972	0	5	7	13	0.000	0.167	30
2129	25	155.60	147.10	52435	0	5	6	14	0.000	0.167	30
2130	25	170.44	160.18	57098	5	8	1	11	0.200	0.286	28
2131	25	144.72	137.02	48841	15	3	3	4	0.600	0.231	13
2120	5	185.60	175.29	62484	0	0	0	5	0.000	0.000	5
2121	25	174.20	161.70	57641	0	3	2	20	0.000	0.107	28
2122	23	151.78	141.54	50453	1	1	4	17	0.043	0.043	23
2123	25	173.04	161.22	57469	2	2	1	20	0.080	0.080	25
2125	25	176.56	163.08	58133	3	2	4	16	0.120	0.083	24
2126	25	171.20	158.30	56429	3	2	3	17	0.120	0.083	24
all	290				38	38	37	177			290

[a] Values in 2002 are an average based on females that will spawn the night after capture and those that spawned two nights before (Lo and Macewicz 2002; Chen et al. 2003).
[b] Number adjusted during biomass estimation per Picquelle and Stauffer 1985; in 2001 and 2002 values equal actual number of mature analyzed .
[c] These females will spawn the night after capture because their ovaries contained migratory-nucleus stage oocytes (Lo and Macewicz 2002, Chen et al. 2003).

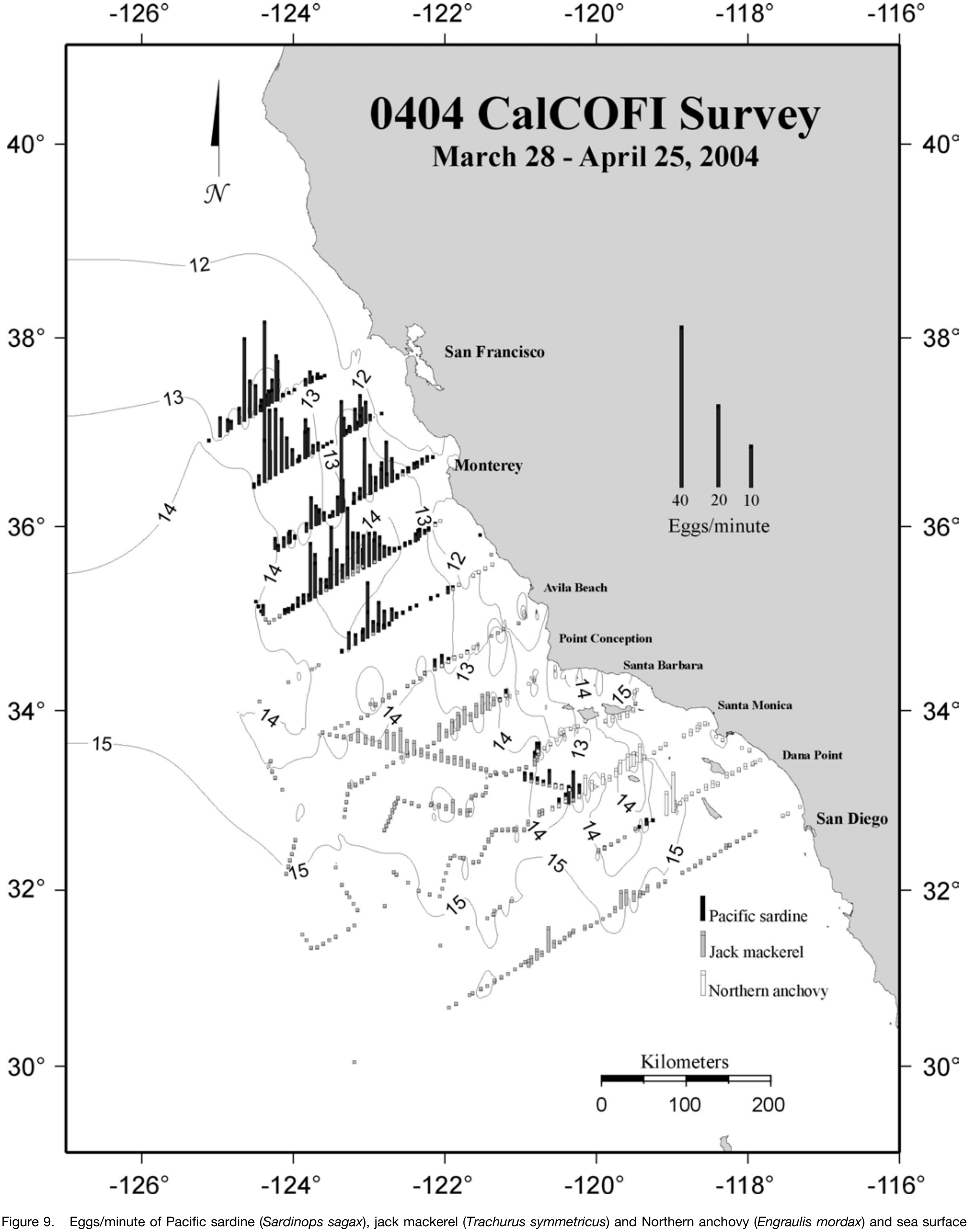

Figure 9. Eggs/minute of Pacific sardine (*Sardinops sagax*), jack mackerel (*Trachurus symmetricus*) and Northern anchovy (*Engraulis mordax*) and sea surface temperature isotherms in 2004.

TABLE 6
Estimates of Adult Pacific Sardine (*Sardinops sagax*) Parameters from Surveys Conducted in 1994, 1997, 2001, 2002, and 2004

		1994	1997	2001	2002	2004
Midpoint date of survey		April 22	March 25	May 1	April 21	April 25
N collections with mature females		37	4	2	6	16
Average surface temperature (°C) at collection locations		14.36	14.28	12.95	12.75	13.59
Female fraction by weight	R	0.538	0.592	0.677	0.385	0.618
Mature female weight (grams):						
with ovary	W_f	82.53	127.76	79.08	159.25	166.99
without ovary	W_{of}	79.33	119.64	75.17	147.86	156.29
Batch fecundity[a]	F	24283	42003	22456	54403	55711
N mature females analyzed[b]		583	77	9	23	290
Spawning fraction of mature females[c]	S	0.073	0.133	0.111	0.174	0.131
Spawning fraction of active females[d]	S_a	0.131	0.130	0.111	0.174	0.131
Daily specific fecundity	RSF/W	11.5	25.9	21.3	22.9	27.0
Standard length (mm) females						
mean		176	221	185	236	243
min.		131	187	161	216	142
max.		284	261	199	250	278
Standard length (mm) males						
mean		175	209	172	233	238
min.		128	129	160	213	171
max.		283	236	188	250	271

[a] 1994–2001 estimates were calculated using $F_b = -10858 + 439.53W_{of}$, (Macewicz et al. 1996); 2004 estimate calculated using $F_b = 356.46W_{of}$ (Lo and Macewicz 2004).

[b] Mature females include females that are active and those that are postbreeding (incapable of further spawning this season).

[c] Fractions in 1994, 1997, and 2004 are based on females that spawned the night before capture and the number of mature females adjusted (Picquelle and Stauffer 1985). The 2001 fraction is based on one spawning female; the 2002 fraction is an average of two nights (Lo and Macewicz 2002); and the number of mature females was not adjusted in either 2001 or 2002.

[d] Active mature females are capable of spawning and have ovaries containing oocytes with yolk or postovulatory follicles less than 60 hours old. Calculation does not adjust the number of active mature females.

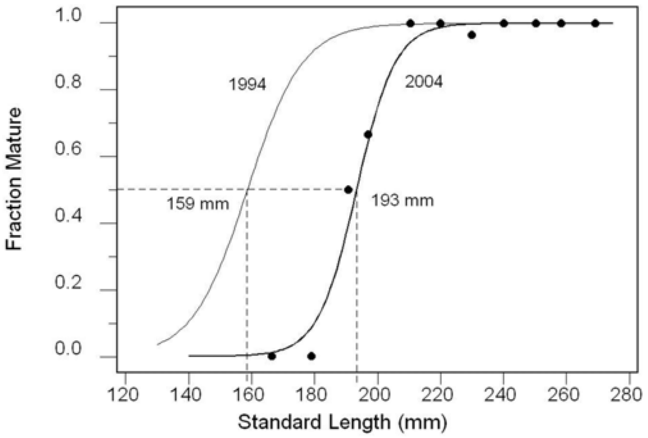

Figure 10. Fraction of Pacific sardine (*Sardinops sagax*) females that were sexually mature as a function of standard length. 2004 logistic curve parameters are $a = -31.605$ and $b = 0.16347$. Symbols represent actual fraction mature within 10 mm length classes for 2004. 1994 logistic curve parameters were $a = -18.16$ and $b = 0.1145$ (Macewicz et al. 1996).

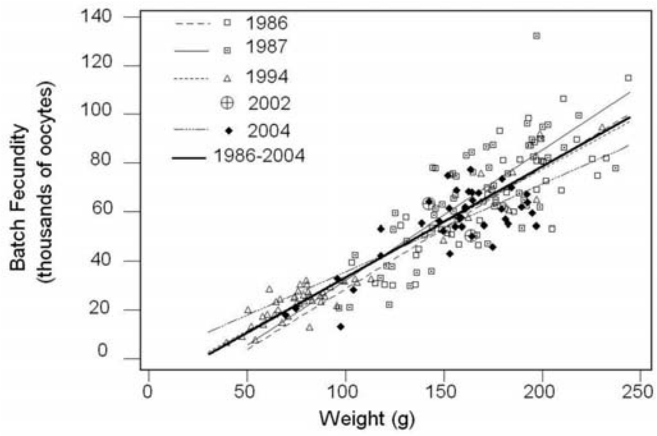

Figure 11. Batch fecundity (F_b) of Pacific sardine (*Sardinops sagax*) as a function of female weight (W_{of}, without ovary) for 191 females from trawl surveys in 1986–2004; fitted regression is $F_b = -12042 + 452.69\ W_{of}$, where $r^2 = 0.799$ (bold line). 1986, 1987, and 1994 (Macewicz et al. 1996) and 2004 (Lo and Macewicz 2004) regression lines are plotted for comparison.

using the daily specific fecundity (number of eggs/population weight (g)/day) of 21.86 (tab. 3).

The estimates of spawning biomass of Pacific sardine in 1994–2004 are 127,000 mt, 80,000 mt, 83,000 mt, 410,000 mt, 314,000 mt, 282,000 mt, 1.06 million mt, 791,000 mt, 206,000 mt, 485,000 mt, and 300,000 mt, respectively (tab. 3, fig. 12). Therefore, the estimate of spawning biomass fluctuated and tripled from 1994 to 2004. The size of the high-density area varied from 57,525 km^2 in 2000 to 130,890 km^2 in 1999 excluding 1994, which included Mexican waters, and 1995 and 1998, when the stratification methods were different from those used in other years.

Spawning Biomass from the Stock Assessment Model

The time series of SSB was around 1 million mt for biological years 1996–2005[11] which is much higher than most of the DEPM spawning biomass (fig. 12). An approximate simple t statistic was computed for each year: $t = (DEPM\text{-}SSB)/sqrt([SE(DEPM)]^2 + [SE(SSB)]^2)$. Except for 2000, 2001, and 2003, all t values were less than –2.5, which is significant at the 5% level with 2 d.f. (in reality, the degree of freedom should be larger). This means for those years with a t value <–2.5, the population mean of SSB was significantly higher than that of DEPM at the 5% level. Using the criterion of overlapped confidence intervals is not recommended because this decision-making process based on overlapped confidence intervals is likely to lead to the conclusion that there is no difference even when there is (Lo 1994), e.g. 1997 and 2004. Because the DEPM estimates were computed from field data, these differences indicate that the procedures of both methods should be examined (see discussion section).

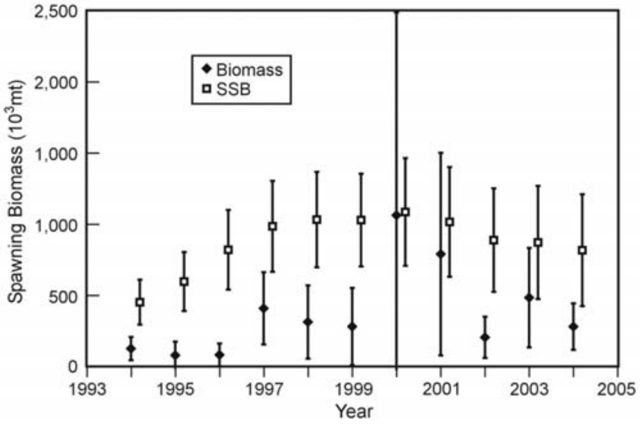

Figure 12. Time series of the estimates of spawning biomass of Pacific sardine (*Sardinops sagax*) off California from DEPM (biomass) and the estimates of spawning stock biomass (SSB) from the ASAP model (Conser et al. 2004). Lines indicate ± 2 standard error.

DISCUSSION

Eggs

Density. Developmental stage-specific egg densities are the basis for estimation of the egg-mortality curve and, thus, the egg production at age 0. On the population level, the density of eggs decreases as the stage increases. However, for Pacific sardines, the egg density seems always to peak at stage 6 (e.g. fig. 4 and Lo et al. 1996)[7, 8, 9, 10], possibly because the spatial distribution of stage 6 eggs is less aggregate than early stages, and stage 6 eggs are still abundant enough for the current sampling intensity. This hypothesis needs to be tested with available data.

Production (P_0). We used a weighted nonlinear regression to estimate P_0. A generalized additive model (GAM) has been used to estimate the annual egg production of Atlantic mackerel (*Scomber scombrus*) (Augustin et al. 1998) and the daily egg production of Atlantic mackerel (*Scomber scombrus*) and horse mackerels (*Trachurus trachurus*) (Borchers et al. 1997; ICES 2003a) and Atlanto-Iberian sardine (*Sardina pilchardus*) and anchovy (*Engraulis encrasicolus*) (ICES 2003b; Stratoudakis et al. 2004). Comparisons between the two procedures for estimating P_0 of sardine and anchovy off Spain and Portugal indicate that although the GAM takes into consideration the spatial distribution of eggs and environmental variables, while the weighted nonlinear regression does not, the point estimates of P_0 from these two methods are similar (fig. 13; ICES 2003b).

A Bayesian procedure has been considered for P_0 in Region 1. The estimate is a weighted average of P_0 of the current year and that of the prior distribution where the weight is the inverse of each variance. As the prior distribution of P_0 is hard to obtain, we opted to use the estimate of P_0 of the previous year as the prior. Therefore, the Bayesian estimate of P_0 becomes the weighted average of P_0 of the current year and P_0 of the previous year. Preliminary work indicated that the time series of Bayesian estimates is much smoother than that of the individual annual estimates in Region 1 from 1997–2004 (fig. 14). The major difference between these two estimates of P_0 was in 2000; the estimate using the Bayesian procedure was much lower than the conventional method, primarily due to the large standard error of the estimate of P_0 from the nonlinear regression in 2000.

Catch Ratio between CUFES and CalVET (E). The 2004 catch ratio between CUFES and CalVET was 0.22, similar to those since 1997 but quite different from the 1996 estimate of 0.73 (fig. 15). The higher ratio in 1996 indicates that the water was more stratified because more eggs were collected at the 3 m CUFES depth. In theory, if there is complete mixing of the water column, the catch ratio would simply be the ratio of the volumes of water filtered by the different nets (Lo et al. 2001). In our study, the data indicated that the catch ratio is positively correlated with the SST, perhaps reflecting increased stratification at higher SST. The only exception to the relationship was in 1999 when the SST was low (12.5°C) and the catch ratio remained similar to those of other years.

A mixing model with environmental covariates for converting CUFES counts to full water column counts has been developed to determine whether CUFES may be used as the primary egg sampler (Sundby 1983; Williams et al. 1983; ICES 2002; ICES 2003b), but the results were not satisfactory. Additional research is currently underway to provide more conclusive results on

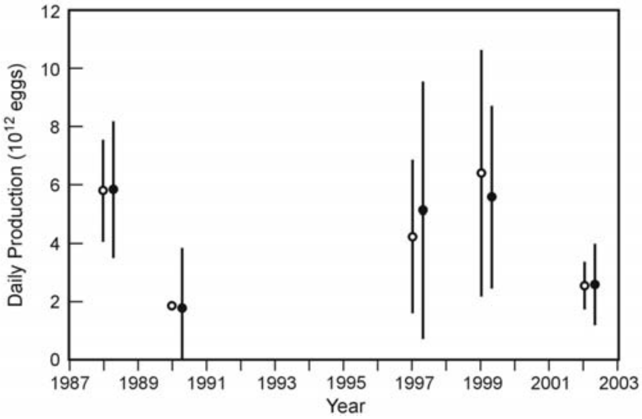

Figure 13. Time-series of estimates of sardine (*Sardina pilchardus*) daily egg production based on the new GAM method (left) and the traditional method (right) for Atlanto-Iberian surveys. Lines are approximate 95% confidence intervals (2SE), which for the traditional method are based on an assumed normal distribution and in the GAM-method on a log-normal distribution. Traditional method estimates have been shifted to the right for presentation. GAM SE is not available in 1990. (Table 2.3.1.3, in ICES 2003b).

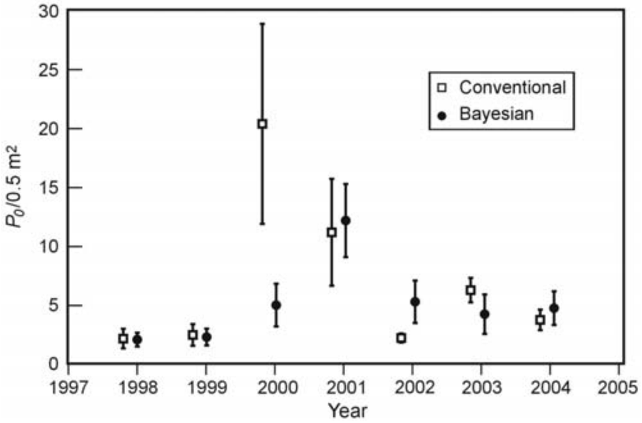

Figure 14. Estimates of Pacific sardine (*Sardinops sagax*) egg production (P_0/0.05 m^2) and ± one standard error using the conventional and the Bayesian method for the high density area (Region 1), 1998–2004.

the applicability of CUFES as a quantitative sampler of egg abundance in the water column[14].

Adaptive Allocation Sampling. The spatial distribution of Pacific sardine eggs varies from year to year (figs. 7–9). The adaptive allocation sampling design, using the eggs collected by the CUFES as a guide, allowed us to allocate CalVET tows where eggs were mostly likely to be found. The efficiency of this survey design was confirmed by data collected in years after 1997 (Lo et al. 2001; Smith et al. 2004). For example, even though the number of net tows used in the 2004 survey was only 18% of that used in 1994, when a conventional survey design was used, the precision of P_0 was similar between these two surveys (tab. 7). A similar adaptive allocation sampling strategy has been used in the Iberian DEPM survey since 2002 (ICES 2002, 2003b).

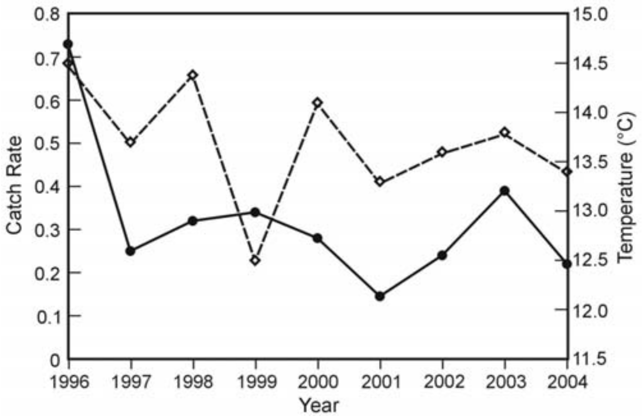

Figure 15. Catch ratio for Pacific sardine (*Sardinops sagax*) (eggs/min to eggs/tow, circle) and sea surface temperature (°C, diamond), 1996–2004.

Spatial Distribution of Pacific Sardine, Jack Mackerel and Northern Anchovy Eggs

The spatial distribution of Pacific sardine spawning fluctuates from year to year, but it consistently occurs within 12°C–14°C SST. It appears that the bulk of the spawning distribution is located within these temperature limits (figs. 7–9). Checkley et al. (2000) characterized the spawning habitat of Pacific sardine as the transition zone between the colder, more saline, upwelled inshore waters and the warmer, less saline waters of the California Current for the years 1996 and 1997. Checkley et al. (2000) also suggested that Pacific sardine and northern anchovy spawn in different types of water; the Pacific sardines occupy the transition zone while northern anchovies spawn in water characterized by upwelled water, which can be either recently upwelled (cooler) water or older upwelled (warmer) water, which is identified by a higher salinity. Temperature salinity plots of the years 1997 to 2002 uphold these trends seen for Pacific sardine and northern anchovy but do not show a distinct trend for jack mackerel (D. Griffith, unpub. data), which tends to span both water types with no relative affinity to either. Jack mackerel spawn in slightly warmer waters but salinity does not appear to be a factor.

Lynn (2002) examined the 1996–1999 Pacific sardine egg distributions off California together with SST and the mean volume backscatter strength (MVBS), which was measured by a 150 kHz acoustic Doppler current profiler (ADCP), a strong indicator of zooplankton volume. He indicated that the inshore distribution of Pacific sardine spawning appears to be limited by the low temperatures of freshly upwelled waters and, in some years (e.g. 1997), the abrupt offshore decrease in MVBS coincides with the offshore boundary of Pacific sardine eggs. Although the MVBS data were not included in our analysis, it appears that SST, salinity, and plankton

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[14] A. Uriarte, pers. comm.

TABLE 7
Pacific Sardine (*Sardinops sagax*) Daily Egg Production (P_0) from a Conventional Survey (1994), Compared with an Adaptive Allocation Sampling in 2004

Year: 1994		**Year: 2004**	
Area	380,175 km^2	Area	320,619 km^2
CalVET tows		CalVET tows	
Total	684	Total	124
Positive for eggs	72	Positive for eggs	67
Positive percent	11	Positive percent	54
CUFES samples	None	CUFES samples	
		Total	781
		Percent positive	32
		High density area	87
		Low density area	15
Daily egg production		Daily egg production	
P_0	0.176/0.05 m^2	P_0	0.96/0.05 m^2
CV	0.22	CV	0.24
Spawning biomass:	117,593 mt	Spawning biomass	281,639 mt

volume all are related to the Pacific sardine egg distributions. The effect of temperature limits on Pacific sardine spawning was especially apparent during the El Niño year of 1998 where the transition zone was drastically narrowed and pushed inshore, with little or no coastal upwelling.

Adult Reproductive Parameters

We estimated the adult parameters for the surveys in 1997, 2001, 2002, and 2004 (tab. 6). Adult size varied by location over the years (tabs. 2 and 5, fig. 3). In 1986–1988, when biomass was low, the average weight of mature females was 154.8–199.9 g (Lo et al. 1996), and adults were caught close to shore or near the islands (fig. 3). By 1994, the sardine population had expanded and the average female weight was small (82.5 g) except for two offshore collections (32°N and 118°W) with mean female weights of 192.9 and 215.5 g (Macewicz et al. 1996). Since 1994, larger females have appeared offshore, and smaller females near shore or close to the islands (tabs. 2 and 5). The length at 50% maturity has increased from 159 mm (age 1) in 1994 to 193 mm (age 2) in 2004 (fig. 10; age estimates from Butler et al. 1996). The increase in length at 50% maturity may be due to location of sampling (most were inshore in 1994 but offshore in 2004; fig. 3), a delay in maturation because of increasing population size, different growth rates, and/or sampling fish schools which migrate through the survey area. In order to distinguish among these, we need to increase the number of samples of adults to cover the entire spawning area.

Spawning fraction can also be expressed as the spawning rate of active females (S_a) times the fraction of active females: $S = S_a\ (N_a\ / N_m)$ where N_a is the number of active females and N_m is the number of all mature females, including active and postbreeding females. Macewicz et al. (1996) found that the average fraction of active females spawning per day, based on females spawning the night before capture, was 0.137 during 1986–1994. The average of the fraction of active females spawning the night before capture in 1997 and 2004 was 0.132 (tab. 6); the estimate in 2002, 0.174, was high due to a bias introduced by the survey design[8]. Hence, the estimate of spawning fraction for active females (S_a) is fairly stable, averaging 0.13. However, the fraction of active females changes through the spawning season and is close to 100% during peak spawning. If ovary samples are unavailable for histological analysis, we recommend setting S to 0.13. If samples are not taken during peak spawning, or if the spawning population is patchily distributed (figs. 7–9) and adults are only sampled in Region 1, an estimate of the fraction of active females by other methods such as port sampling would be necessary to adjust S downward. Again, increasing the quantity of adult samples and number of locations from which they are collected to cover the entire area of egg production should minimize bias in estimation of S.

The relationship of female weight (W_{of}) and batch fecundity is similar among the years 1986–2004 (fig. 11). If females with ovaries containing hydrated or migratory-nucleus stage oocytes are not available, we recommend using the overall equation ($F_b = -12042 + 452.69W_{of}$) to estimate fecundity of each mature female used in the spawning biomass computation.

Spawning Biomass

The fluctuation of spawning biomass among years could be due to 1) a real change of spawning biomass off California; 2) migration of the adult population along the western coast of North America; 3) change in the estimates of egg production, P_0, for years when trawl surveys were not conducted and an average of spawning fraction was used; and 4) any combination of the above. The 2004 estimate of spawning biomass is considerably lower than that in 2003 but similar to 2002. These differences are primarily due to the change of the egg production estimate, 0.96 eggs/0.05 m^2 over a smaller Region 1 area in 2004 compared to 1.52 eggs/0.05 m^2 in 2003 and 0.728 eggs/0.05 m^2 in 2002 (tab. 3). The daily specific fecundity of 21.86 eggs/g/day used for the 2004 estimate of spawning biomass was based on trawl samples taken from Region 1, but the daily egg production per day for the entire survey area was a weighted average of the estimates from regions with high and low egg density. Thus, the spawning biomass may have been underestimated because the daily specific fecundity may be lower in Region 2 than Region 1. The degree of underestimation may be minimal unless the daily specific fecundity or the spawning fraction in Region 2 was substantially lower than that in Region 1, as the number of eggs produced per day in Region 1 was 87% of the total produced per day in the entire survey area. To estimate the degree of bias of the spawning biomass estimate when trawl samples are taken only from Region 1, it is necessary to collect adult samples in the low-density area in future years. Data from adult samples in the low-density area will be also useful to ascertain the presence of an adult population because a low density of eggs may result from either a low abundance of adults or a high abundance of adults with low spawning activities.

Sardine Stock Assessment and Spawning Biomass

The DEPM estimate is used in assessments of the Pacific sardine as an index of abundance, and it has not been treated in the assessment model as an absolute measure of spawning biomass. Nevertheless, it is important to compare this direct measure of spawning biomass to that derived from age-based assessment models to see what can be learned regarding both the DEPM and the assessment models. When we did this (fig. 12), we found that, except for the 2000, 2001, and 2003 surveys, the population means of SSB estimated by the sardine stock assessment model were significantly higher than those of the DEPM biomass estimates, despite the high variance in both of SSB and the DEPM estimates.

A variety of potential biases exist in the application of the DEPM that could lead to underestimating spawning biomass (Deriso et al. 1996). These include movement of postspawning adults out of the sampling area, egg contagion affecting the slope of egg-embryonic mortality curve, changes in the age of first maturity, failure of the DEPM survey to cover all spawning habitats, and changes in the seasonality of spawning. On the other hand, the potentially biased age composition (Deriso et al. 1996), and/or the change of the maturity ogive to older fish in 2004 from younger fish in 1994 (fig. 10), may result in an overestimate of the SSB from the stock assessment model and thus affect the inter-comparisons of the estimates from the two methods. We conclude that the comparison between DEPM and the current ASAP model indicates that it is necessary to address the basis for the differences in estimates between methods and thereby improve our understanding of sardine biology and improve future DEPM and assessment models.

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PACIFIC SARDINE (*SARDINOPS SAGAX*) STOCK DISCRIMINATION OFF THE WEST COAST OF BAJA CALIFORNIA AND SOUTHERN CALIFORNIA USING OTOLITH MORPHOMETRY

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ABSTRACT

The hypothesis that there are three Pacific sardine (*Sardinops sagax*) stocks along the west coasts of Baja California and southern California was evaluated using multivariate discriminant analysis of otolith morphometric variables. Four synoptic data sets were analyzed to test the three-stock hypothesis: warm Magdalena Bay (Warm MB), temperate Magdalena Bay (Temp MB), temperate Ensenada (Temp EN), and cold Ensenada (Cold EN). A gradual increase in the overlap index (Wilks´ Lambda values) reflected the relative degree of similarity among the groups when all comparisons were considered. The Warm MB was the most differentiated group from the others, particularly the Cold EN. The highest degree of similarity was found among the two temperate groups (Temp MB and Temp EN), and they could not be significantly separated in 68% of the repeated tests. Our results support the existence of the three Pacific sardine stocks in the study area and are consistent with previous findings obtained using different methodologies, e.g. temperature-at-catch data.

INTRODUCTION

The Pacific sardine (*Sardinops sagax*) has a wide geographic distribution, ranging from Southeast Alaska to the southern tip of the Baja California Peninsula and into the Gulf of California (Kramer and Smith 1971; Parrish et al. 1989). It is important to know whether this population consists of one or several stocks and, if multiple stocks do exist, to define their corresponding distributions (Clark 1947). The identification of discrete unit stocks is a basic requirement for fisheries management (Cushing 1968).

It is possible that environmental pressure could segregate the Pacific sardine population into several stocks. The following definition of stock is used in this paper: a unit stock can be thought of as a group of sardines with different reproductive seasons or spawning areas which should be managed independently. For management purposes, a unit stock does not necessarily correspond to a genetically distinct group (Saila and Martin 1985).

Within each of the large current systems where the sardine occurs, several stocks exist. In the California Current System, the existence of three stocks has been proposed: one off the California coast, the second off the outer Baja California Peninsula, and the third in the Gulf of California (Clark 1947; Vrooman 1964; Mais 1972; Schwartzlose et al. 1999). A fourth stock, the most northern of all, was proposed by Radovich (1982). Identification of these stocks was approached using a variety of methods, including meristics, morphometrics, tags, blood antigens, and population parameters (e.g. differential growth); nevertheless, Hedgecock et al. (1989) found low genetic variability for this species in the Northeast Pacific.

Most recently, Felix-Uraga et al. (2004) provided additional evidence regarding these three groups or stocks of Pacific sardines from Magdalena Bay (México) to San Pedro (USA) based on temperature-at-catch data. Thermal stratification of the sardine population was used to build a conceptual distribution model in space-time for the three sardine groups along the west coast of the Baja California Peninsula and southern California (fig. 1). The conceptual model suggests southward movement of the three groups beginning in winter with the strengthening of the California Current, with all the groups reaching their southern-most distribution in spring. In summer, the northward movement of the three groups begins with the onset of the equatorial countercurrent flow, with all groups reaching their northern-most latitudinal distribution in fall. Figure 2a was taken from Felix-Uraga et al. (2004) and the sea surface temperature (SST) limits (17°C and 22°C) for each putative stock were hand drawn. Figure 2b illustrates the annual

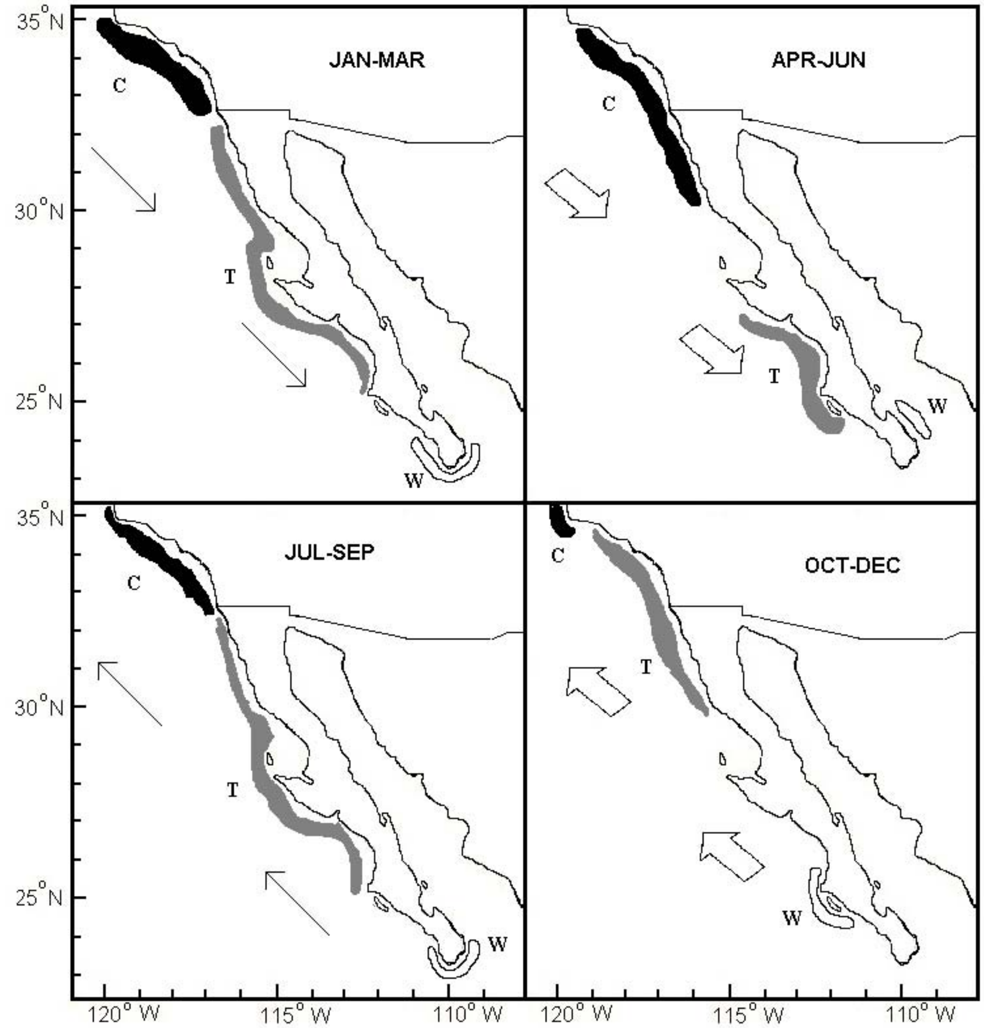
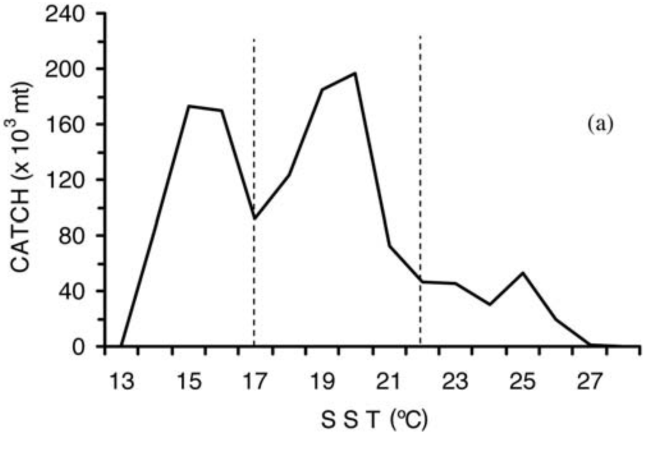


Figure 1. Time-space distribution model of the three-stock hypothesis for Pacific sardines (*Sardinops sagax*): C = cold stock, T = temperate stock, and W = warm stock.



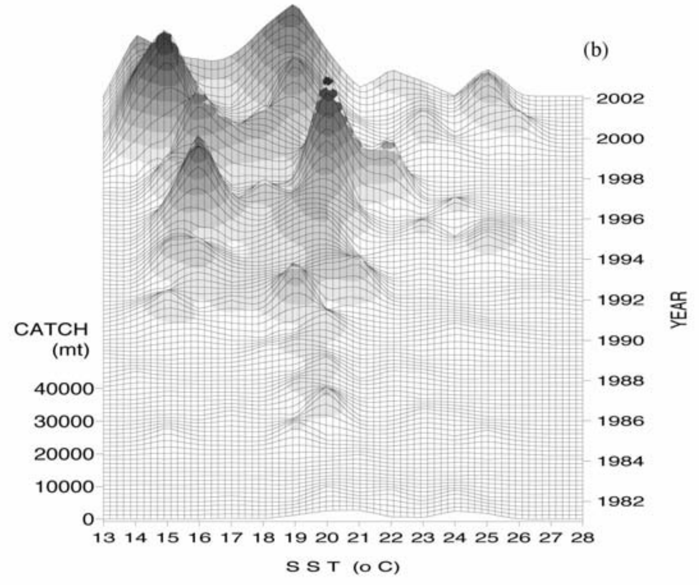


Figure 2. Pacific sardine (*Sardinops sagax*) catches aggregated by 1°C intervals of SST for the four landing ports during 1981–2002: (a) whole period; (b) yearly distributed.

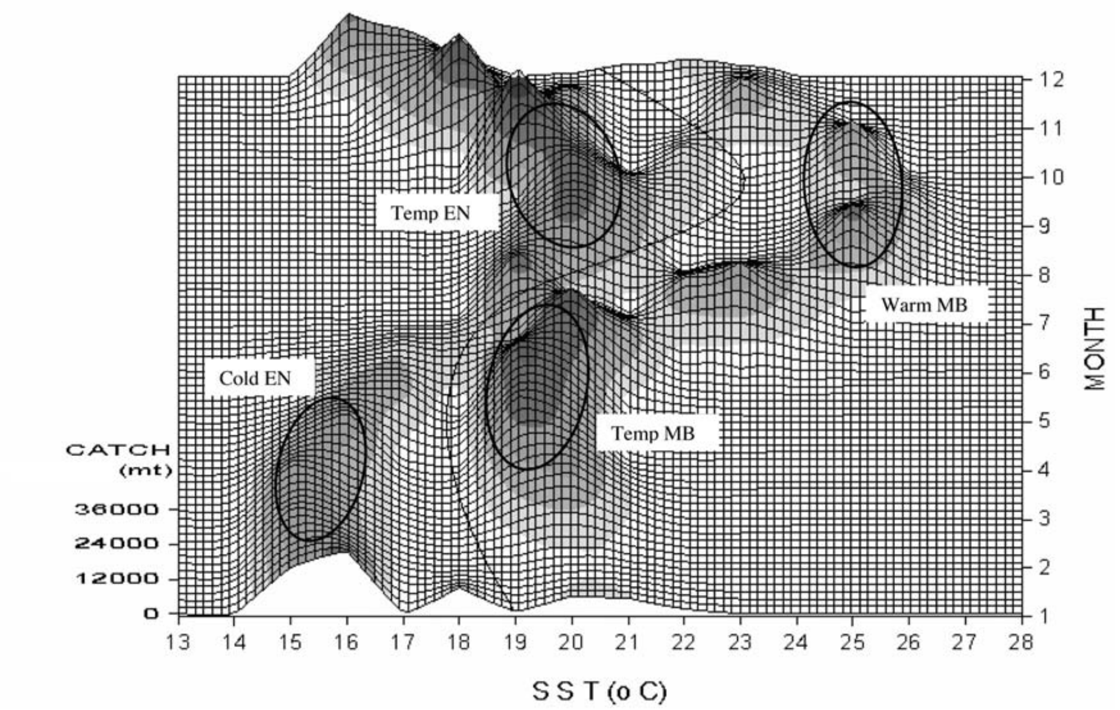


Figure 3. Monthly distribution of Pacific sardine (*Sardinops sagax*) catches aggregated by 1°C intervals of SST. Selected data groups for further analysis (ellipses) correspond to supposed different stocks depending on climate conditions (warm, temperate and cold) and landing port: Ensenada at left and Magdalena Bay at right of the curved line.

catches from Magdalena Bay to San Pedro, 1981 to 2002, grouped by one-degree increments of SST; the annual pattern for the putative stocks is consistent over time.

The development of image analysis systems has facilitated diversification of morphometric methods and expanded the potential of morphometry as a tool for stock identification, providing accurate and efficient measures that traditional methods have not been able to provide (Cadrin and Friedland 1999). Otolith shape analysis has been used for stock determination in several fish species (Campana and Casselman 1993; Bolles and Begg 2000; De Vries et al. 2002). Detection of morphometric differences in fish populations within their geographical range can indicate the presence of stock structure (Thresher 1999; De La Cruz-Agüero and García-Rodríguez 2004). In this paper, we test Felix-Uraga et al.'s (2004) three-stock hypothesis using otolith image analysis in combination with multivariate statistical analysis, in an attempt to distinguish the putative sardine stocks.

MATERIAL AND METHODS

The contour plot of catch by sea surface temperature (SST) and month for Magdalena Bay and Ensenada, originally published in Felix-Uraga et al. (2004; their fig. 4), was redrawn as a three dimensional plot (fig. 3) to further illustrate the hypothesis of three sardine stocks in these locations. Catches to the left of the thin separating curve (freehand traced) correspond to Ensenada, and those to the right of the curve correspond to Magdalena Bay.

To test the three-stock hypothesis, four data groups corresponding to different combinations of locations and SST intervals were identified. The warm stock was present only in Magdalena Bay (Warm MB) at SSTs higher than 22°C and was captured mainly from July to December. The temperate stock, present in Magdalena Bay (Temp MB) at SSTs between 17° and 22°C, was captured primarily from February to June and, because it shares the same SST range is considered the same stock as that observed from July to November off Ensenada and San Pedro (Temp EN). The cold stock (Cold EN) was present in Ensenada and San Pedro at an SST interval of 13°–17°C and was caught mainly from December to May.

This *a priori* stock classification was considered for the application of multivariate discriminant analysis (MDA) to the otolith morphometric variables. The ellipses in Figure 3 indicate that the months considered have a higher probability of representing each one of the three sardine stocks off Baja California and southern California. Synoptic samples of sagittal otoliths from these months and locations were used for the morphometric analysis (August to October for Warm MB and Temp EN; March to May for Temp MB; February to April for Cold EN).

Whole sagittae were imaged, sulcus down at 12x magnification, and digitally measured using Sigma Scan Pro

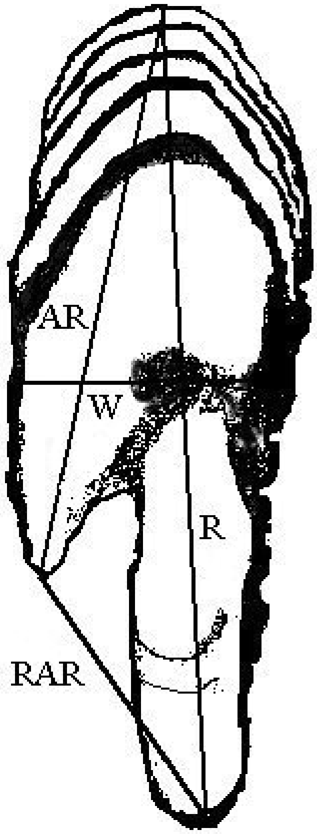


Figure 4. Morphometry of Pacific sardine (*Sardinops sagax*) otolith: AR = Distance from antirostrum to the posterior edge. R= distance from posterior edge to rostrum. RAR = distance of rostrum to antirostrum. W = otolith width crossing by focus.

4.0 software. Four distances (distance from antirostrum to the posterior edge (AR); distance from posterior edge to rostrum (R); distance of rostrum to antirostrum (RAR); otolith width crossing by focus (W)) were measured on the distal side of the left otolith of each pair extracted from sardines sampled in Magdalena Bay and Ensenada from 1994 to 2002 (fig. 4). The right otolith was measured only when the left was broken. Otolith morphometric samples were restricted to one-year-old sardines to limit variability associated with age and size of fishes and because this was the most abundant age-group in the landings.

MDA was used to compare the otolith morphometric variables from the three putative sardine stocks. These variables were examined for normality using the Kolmogorov-Smirnov (K-S) test (Zar 1996) prior to the Wilks´ Lambda test (Tabachnick and Fidell 1989) for discriminant significance. Statistica 6.1 software was used for these procedures.

The MDA based on otolith morphometric variables from the four synoptic samples (fig. 3) was performed for the six possible paired comparisons. To prevent bias from unbalanced sample sizes, and to obtain a more robust analysis, each synoptic sample was randomly subsampled 50 times, taking a subset of 50 non-repeated otolith morphometric variables each time. Fifty statistical tests for the six paired comparisons were performed, and the frequency distribution of the Wilks´ Lambda values for each comparison was obtained.

To determine whether differences exist within each of the four synoptic groups, MDA was performed based on two balanced, non-replacement, random sub-samples taken from each group, which were then compared.

Accuracy of the discriminant classification of otoliths from the three putative stocks was tested using a random sample (*n* = 100 otoliths) from each group. The temperate stock sample was integrated using 50 otoliths from both temperate locations (Magdalena Bay and Ensenada).

RESULTS

Synoptic samples for otoliths measured from Magdalena Bay and Ensenada, 1994 to 2002, are shown in Table 1. Lack of data at Magdalena Bay from the end of 1997

TABLE 1
Monthly number of Pacific sardine (*Sardinops sagax*) otoliths (age group one) sampled from Magdalena Bay and Ensenada, 1994–2002

Month	1994	1995	1996	1997	1998	1999	2000	2001	2002	Total
Magdalena Bay										
March	20	21	9	19			79	76	21	
April	46			93				57	100	
May	38	11	59	56	35			85	44	**869**
August	39	39	14					16	54	
September	56	56	9					21	10	
October	48	18	16					25		**421**
Ensenada										
February		14	14			66	26	4		
March		11	12	4	5	11	19	26	2	
April		11		1	2	4	8	13	18	**271**
August	25	19	19	7		11	35	10	12	
September	8		2	7	5	4	27			
October	5	25	5	3	1	6	32	20		**288**

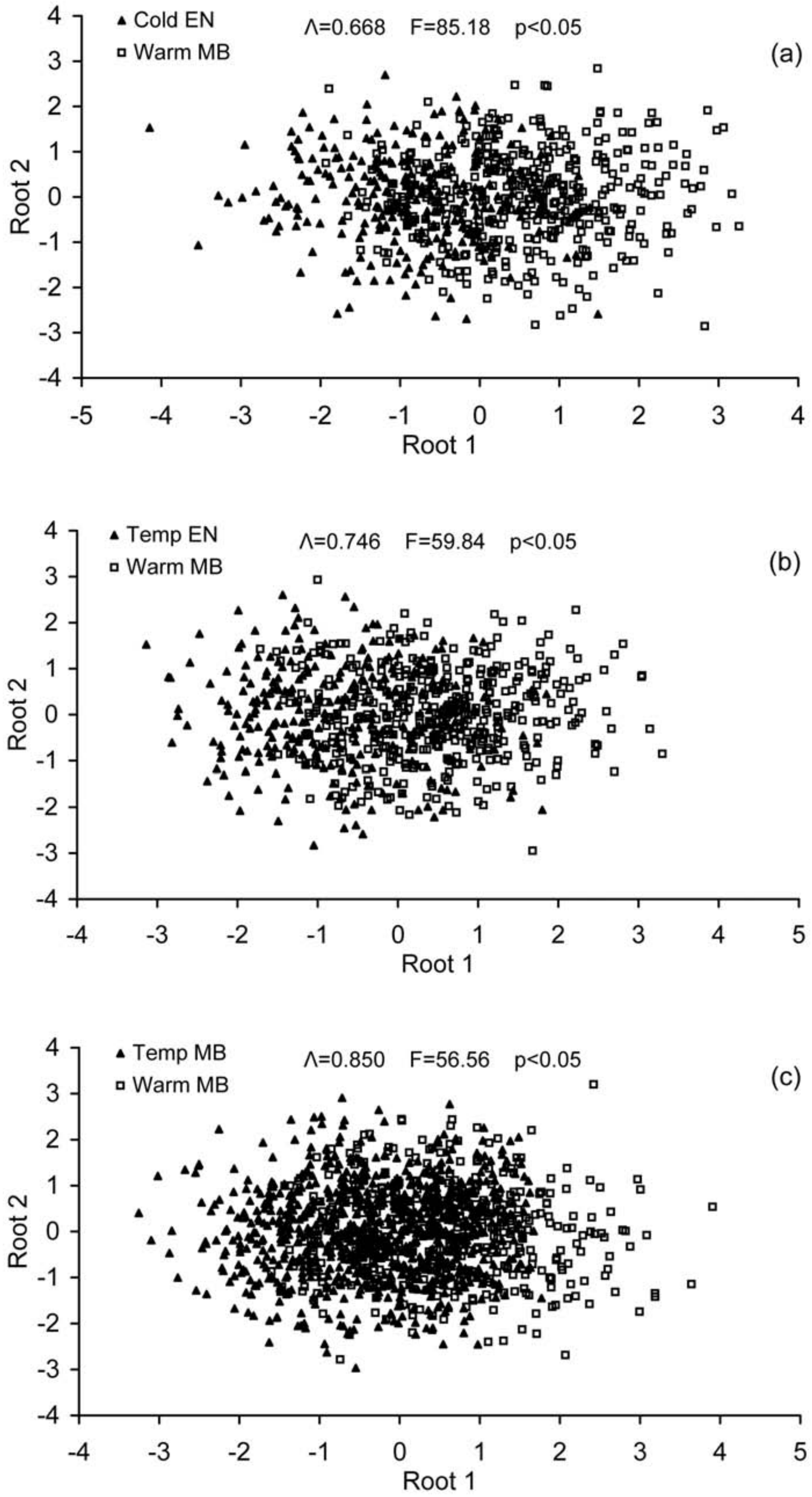


Figure 5. Discriminant scores for each Pacific sardine (*Sardinops sagax*) otolith depending on morphometric variables for Magdalena Bay warm stock (Warm MB) versus: (a) Ensenada cold stock (Cold EN); (b) Ensenada temperate stock (Temp EN); (c) Magdalena Bay temperate stock (Temp MB).

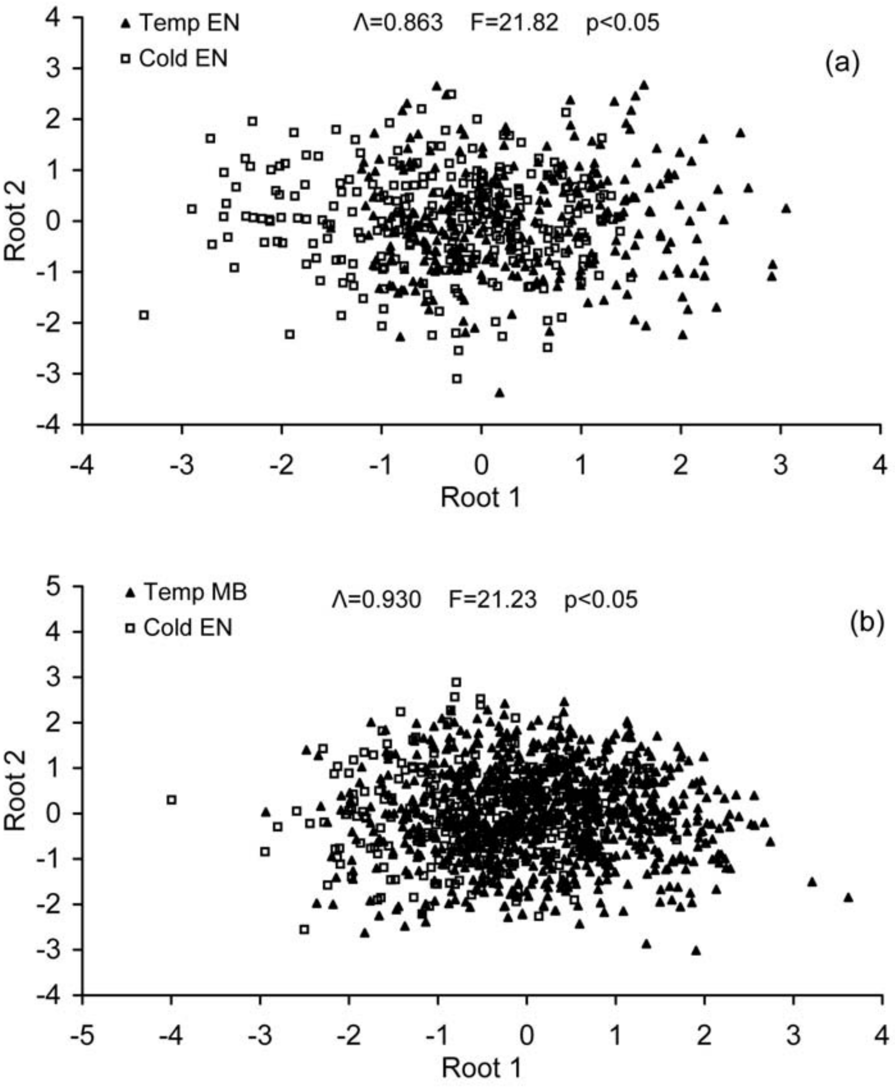


Figure 6. Discriminant scores for each Pacific sardine (*Sardinops sagax*) otolith depending on morphometric variables for Ensenada cold stock (Cold EN) versus: (a) Ensenada temperate stock (Temp EN); (b) Magdalena Bay temperate stock (Temp MB).

until 2000 was due mainly to the El Niño phenomenon, which caused a great decrease in the sardine landings in this area and thus affected our sampling program.

All otolith morphometric variables (AR, R, RAR and W) were normally distributed (K-S, $p > 0.2$). MDA results between the Warm MB and the Cold EN, Temp EN and Temp MB groups revealed significant differences for the first three comparisons (fig. 5a, b and c; tab. 2) since the null hypothesis of a common statistical population was rejected. The lowest degree of overlap ($\Lambda = 0.668$) was observed between the Warm MB and Cold EN stocks. Statistically significant differences were also detected for otolith morphometrics between Cold EN and Temp EN and between Cold EN and Temp MB (fig. 6a and b). However, the amount of overlap increased relative to the three previous comparisons (fig. 5).

TABLE 2

Results of comparisons of Pacific sardine (*Sardinops sagax*) otolith morphometric variables with multiple discriminant analysis

Stock Comparison	Wilks' Lambda	*F*	*p*
Cold EN and Warm MB	0.6684459	85.189	<0.05
Temp EN and Warm MB	0.7462443	59.847	<0.05
Temp MB and Warm MB	0.8502735	56.569	<0.05
Cold EN and Temp EN	0.8638776	21.823	<0.05
Cold EN and Temp MB	0.9308738	21.238	<0.05
Temp MB and Temp EN	0.9694526	9.074	<0.05

For the last comparison (Temp EN and Temp MB), we did not expect to detect any difference, but the MDA also showed significant differences despite a high degree of overlap ($\Lambda = 0.969$; fig. 7).

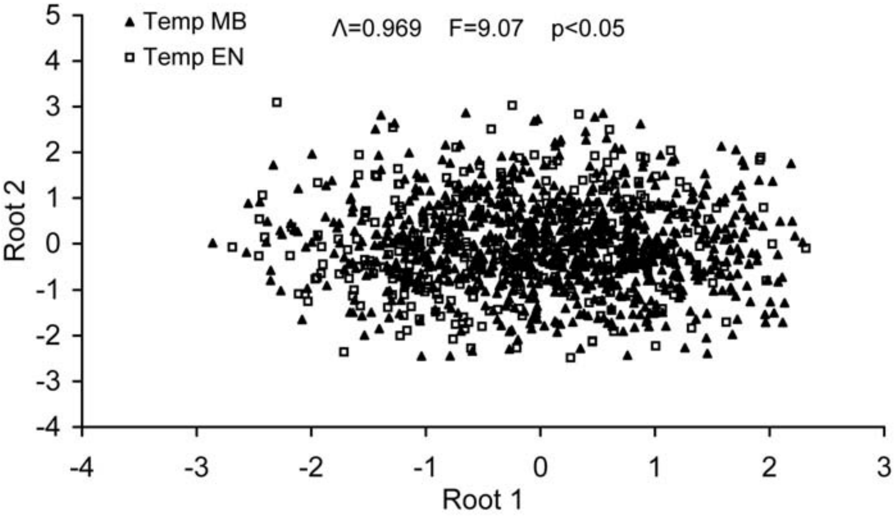


Figure 7. Discriminant scores for each Pacific sardine (*Sardinops sagax*) otolith depending on morphometric variables for Magdalena Bay temperate stock (Temp MB) versus Ensenada temperate stock (Temp EN) for whole period data (1994–2002).

Results of MDA using balanced random samples—presented as frequency distributions of Wilks´ Lambda values for each comparison, average Wilks´ Lambda value, and percentage of non-significant tests—are displayed in Figure 8. A progression from the most dissimilar groups (lower lambdas) to the most similar groups (higher lambdas) was observed. Average lambda values obtained from the 50 tests from the four synoptic samples (subsampled to avoid bias from unbalanced sample sizes) confirmed the results of previous analyses in which all samples were included.

A progression in the percentage of non-significant tests was also observed, from 0% for comparisons between the most dissimilar groups (Cold EN and Warm MB) to 68% for the most similar groups (Temp MB and Temp EN), which were assumed to be the same stock (fig. 8).

The results of the MDA performed for intra-group comparisons were consistent with regard to otolith morphometry because all tests were non-significant ($p > 0.05$), and Wilks´ Lambda values were very close to one (tab. 3).

The MDA test for the three putative stocks was highly significant (Wilks´ Lambda = 0.68, $F_{(8,588)} = 15.42$, $p < 0.05$) and showed that 67% of otoliths from the warm stock (Warm MB), 42% of the temperate stock (Temp MB-EN), and 57% of the cold stock (Cold EN) were well classified; although it was not the objective of this paper to predict group membership from arbitrary otolith samples (tab. 4).

DISCUSSION

Variations in size can lead to spurious results when MDA is used to discriminate stocks, since it can be affected by sampling bias and sample design (Dos Reis et al. 1990). Bolles and Begg (2000) found differences in otolith morphometrics of *Merluccius bilenearis* due to age of the organisms. To reduce bias in size and age, we used otoliths of 1-year-old sardines.

Sampling bias is the most common cause of artificial heterogeneity between groups, and results from the uneven collection of specimens over space or time (Reist 1985). We used a random sub-sampling routine to avoid bias originating from unbalanced sample sizes among groups. The MDA results in this paper performed with two types of samples (total number, and equal number of subsamples by group) were consistent with each other (tabs. 2 and 3).

In morphometric studies, it is also essential to consider confounding variation that may be present due to differences among samples in an age-group, year-class, or specific sex, so as not to mistake stock differences for sample differences (Bolles and Beggs 2000). Confounding variability produced by sex and year-classes was not detected by MDA performed for intragroup subsamples. These results indicate a consistency between otolith variables of different years and sexes.

Results of the MDA agreed with what we expected *a priori*—that three Pacific sardine stocks exist along the west coast of Baja California and California (Felix-Uraga et al. 2004). The MDA comparison having the greatest difference with respect to temperature and distance (Cold EN vs. Warm MB) revealed the lowest overlap ($\Lambda = 0.668$) among all comparisons.

Comparisons between Temp EN and Warm MB, Temp MB and Warm MB, Temp EN and Cold EN, and Temp MB and Cold EN also revealed significant differences among these putative stocks, with indices of overlap gradually increasing between intermediate values (tab. 2). In the comparison of the Temp EN and Temp

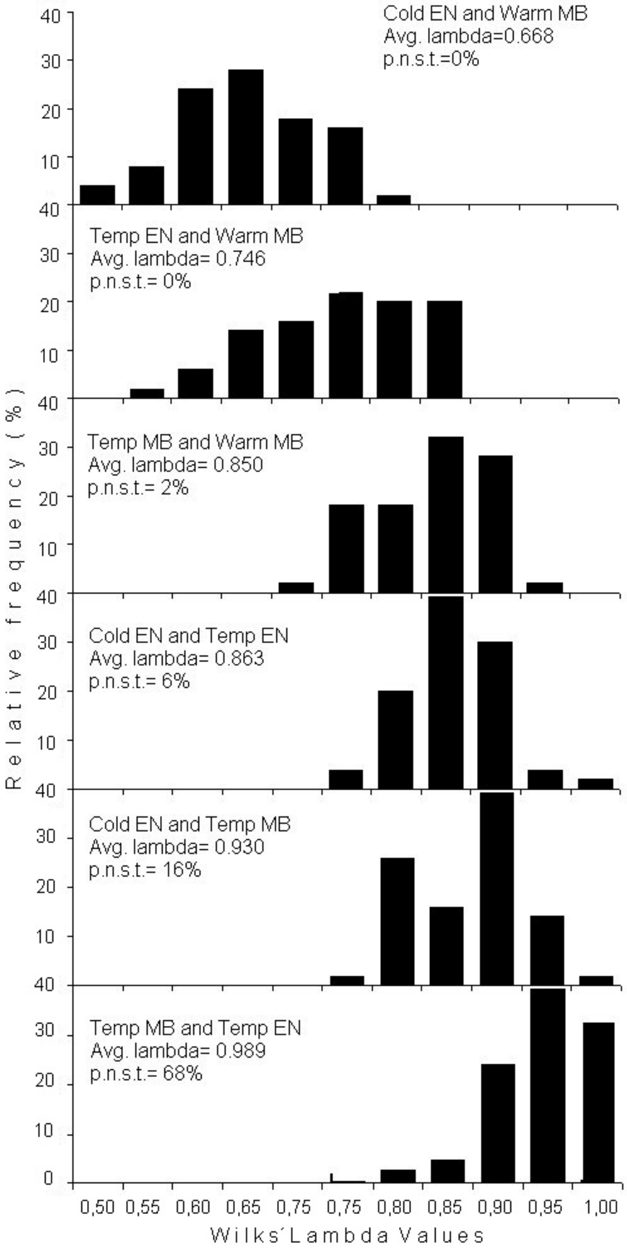


Figure 8. Frequency distributions of resulting Wilks´ Lambda from tests among paired groups. The results of the average Wilks´ Lambda values and the number of non-significant tests are given. p.n.s.t. = percentage of non-significant tests.

TABLE 3
Statistics resulting for intra-stocks discriminant analysis performed with two random balanced samples from each Pacific sardine (*Sardinops sagax*) group

Stock	Wilks´ Lambda	Statistic F(m,n)	Error probability p
Warm MB	0.9892	F (4,415) = 1.133	< 0.3403
Temp MB	0.9918	F (4,863) = 1.792	< 0.1283
Temp EN	0.9785	F (4,283) = 1.554	< 0.1869
Cold EN	0.9790	F (4,265) = 1.421	< 0.2271

TABLE 4
Accuracy of discriminant classification of the otoliths from the three putative Pacific sardine (*Sardinops sagax*) stocks. Numbers of well-classified otoliths are on diagonal

	Number of otoliths classified by group		
Stock	Warm MB	Temp MB-EN	Cold EN
Warm MB	**67**	15	18
Temp MB-EN	32	**42**	26
Cold EN	18	25	**57**

MB groups, which we assumed made up the same stock, the overlap index was the highest among all comparisons ($\Lambda = 0.969$); however, the F-test still indicated a significant difference.

In these six comparisons, the gradual increase in the overlap index reflected the degree of similarity among the stocks. The warm stock of Magdalena Bay (Warm MB) and the cold stock of Ensenada (Cold EN) were the least similar groups to each other. The temperate stock was more similar to the cold stock than the warm stock. Other authors have also considered sardines from the Gulf of California to be the most distinct group in the Northeastern Pacific (Clark 1947; Vrooman 1964; Mais 1972; Radovich 1982).

The highest degree of similarity was found between the two locations of the temperate stock (Temp MB and Temp EN), a result which was expected based on the conceptual model of time-space distribution proposed by Felix-Uraga et al. (2004). Our results support the hypothesis that the temperate stock present in Magdalena Bay during the first half of the year is the same stock present in Ensenada and San Pedro during the second half of the year.

These results provide new evidence in support of the three-stock hypothesis for the Pacific sardine population previously outlined by Clark (1947 and 1952), Vrooman (1964), Mais (1972), Radovich (1982), and Felix-Uraga et al. (2004), regardless of the low genetic variability evidenced for this species (Hedgecock et al. 1989). The stocks defined by temperature-at-catch data have a clear geographic differentiation, although the high percentage of misclassification from otolith morphometrics does not support the possibility that they are genetically different (Solow 1990).

Otolith development occurs under dual regulation: genetic conditions regulate its form, and environmental conditions (mainly temperature) regulate the quantity of material deposited during formation (Lombarte and Lleonart 1993). On this basis, it is reasonable to believe that otolith morphometric differences found among the stocks are determined by local environmental conditions (Hedgecock et al. 1989; Parrish et al. 1989; Lluch-Belda et al. 1991a).

Based on the working definition for fisheries management, a "stock" is a management unit and not a discrete biological population unit. Consequently, fish stocks having different phenotypic (i.e. morphometric) characteristics or life history (i.e. growth) dynamics should be considered separate units and modeled separately for stock assessment and management purposes, regardless of genetic characteristics (Cadrin and Friedland, 1999).

Environmental temperature is considered the most important factor affecting distribution of marine organisms (Lluch-Belda et al. 1991b). Productivity of sardine populations in the different current systems has been associated with interdecadal regime shifts driven by large-scale changes in ocean climate (Rodriguez-Sanchez et al. 2001). The sardine population extends its geographical distribution during warm periods and contracts it during cold ones (Lluch-Belda et al. 1989). The recent increase and expansion of the Pacific sardine population could have resulted in the current three-stock structure, which may only occur when the fish are very abundant and the population extends to its northern limit.

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PACIFIC SARDINE (*SARDINOPS SAGAX*) ABUNDANCE, DISTRIBUTION, AND ECOLOGICAL RELATIONSHIPS IN THE PACIFIC NORTHWEST

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ABSTRACT

During the 1930s and 1940s, Pacific sardines (*Sardinops sagax*) supported an important fishery in Pacific Northwest waters, but after their population crashed in the mid-1950s, they were rarely observed in this region. Starting in the mid-1990s, sardines resumed migrating into Northwest waters to spawn and feed. Pacific sardines now support a relatively large purse seine fishery centered off the Columbia River. From 1994 to 1998, we identified the abundance and distribution of Pacific sardine eggs and larvae in Northwest waters. The highest egg densities were observed in June 1996. During all years, eggs were associated with surface temperatures between 14° and 15°C. From 1998 to 2004, surface-trawl surveys, primarily on the continental shelf, identified the temporal and spatial distribution and abundance patterns of juvenile and adult Pacific sardines. Adult sardines generally do not over-winter off the Northwest, but migrate north from California in the spring (May–June) when surface temperatures exceed 12°C. However, juvenile sardines over-winter in nearshore coastal waters. During most years, few 0-age juveniles were captured, indicating relatively poor spawning success; however, high densities of 0-age sardines were observed in fall of 2003 and 2004, indicating successful spawning. During the summer, sardines are most abundant on the shelf in cool (<16°C) and high salinity (>30 S) coastal waters, with their highest densities occurring in northern Oregon/Washington waters. Sardines are non-selective planktonic filter feeders; prey include copepods, euphausiids, and phytoplankton. Sardines are important prey of Northwest fishes, such as sharks, salmon, Pacific hake (*Merluccius productus*), and jack mackerel (*Trachurus symmetricus*).

INTRODUCTION

The Pacific sardine (*Sardinops sagax*) is frequently a dominant pelagic fish in the California Current. However, over the last several millennia its abundance has fluctuated greatly due to regime shifts in ocean conditions (Ware and Thomson 1991; Baumgartner et al. 1992; McFarlane et al. 2002; Chavez et al. 2003). During peak abundance periods, this sardine population has supported major commercial fisheries. The main population and fishery are centered off central and southern California, but during periods of high abundance and warmer ocean temperatures, a portion of the population either resides off of, or is a transient visitor to, Oregon, Washington, and British Columbia, with some individuals traveling as far north as southern Alaska (Hart 1973; Wing et al. 2000; McFarlane and Beamish 2001). At these times, commercial fisheries for sardines, or pilchards (another common name), also develop in the Pacific Northwest (PNW) and British Columbia.

Sardines were first landed commercially in Oregon during 1935–36 and a year later in Washington, well after the commencement of sardine fisheries in both California and British Columbia (Chapman 1936; Schaefer et al. 1951). Most sardines were landed in Grays Harbor, Washington and Astoria and Coos Bay, Oregon, and were generally rendered to oil and fishmeal. Following the collapse of the sardine population and fishery in the late 1940s, there were few reports of sardines in the PNW. Reid (1960) reported the catch of a single male in Winchester Bay, Oregon in August of 1957. During coastal purse seine surveys off Oregon and Washington from 1979 to 1985, only five sardines were caught between June and September in 1984 off central Oregon (Brodeur and Pearcy 1986; Pearcy and Schoener 1987). Ermakov and Stepanenko (1996) also reported a few sardines captured from research trawls in the PNW during the 1980s. These sporadic occurrences appear to be associated with warm ocean conditions and the anomalous northward advection of southern species associated with El Niños (Pearcy and Schoener 1987).

In 1992, sardine numbers increased dramatically in the PNW (Hargreaves et al. 1994), apparently in response to the 1992–93 El Niño. They continued to increase in abundance and began spawning in PNW waters (Bentley et al. 1996; McFarlane and Beamish 2001). This abrupt change in sardine abundance and distribution in the PNW followed an apparent ocean regime shift in 1989 (McFarlane and Beamish 2001; McFarlane et al. 2002) and coincided with dramatic changes in the overall pelagic fish biomass off the PNW (Emmett and Brodeur 2000).

Forage fishes, including sardines, anchovies, and other small pelagic fish species, dominate the pelagic ecosystems in many coastal upwelling regions (Crawford 1987). Indeed, pelagic fish can often exert a major control on the trophic dynamics of upwelling ecosystems that fall under the category of midtrophic-level, "wasp-waist" populations (Cury et al. 2000). Sardines are omnivores that feed on both phytoplankton and zooplankton (James 1988, van der Lingen 2002) and can consume a substantial proportion of the primary and secondary production in the southern California Current during years of high abundance (Lasker 1970). However, there have been few studies of the Pacific sardine diet in the northern California Current (e.g., Hart and Wailes 1931, McFarlane and Beamish 2001) and none in the PNW region. During periods of high abundance all sardine life stages are likely to be eaten by a variety of predators that normally consume other forage species. For example, Chapman (1936) showed that sardines were important prey for both coho (*Oncorhynchus kisutch*) and Chinook salmon (*O. tshawytscha*) when they were abundant in the 1930s. There are presently no studies that have identified sardine predators in the northern California Current during its present population resurgence.

To effectively manage fish stocks, it is necessary to know the basic biological parameters of a stock, such as size, age, feeding habits, and migrational characteristics. Therefore, using a variety of data sources and based on sampling from 1977 to 2004, we describe the abundance, spatial and temporal distribution, size and age composition, life history, and ecological relations of sardines during the recent population increase off the coasts of Washington and Oregon.

DATA AND METHODS

Commercial Catch and Age Distribution, 1999–2003

Both the Oregon and Washington Departments of Fish and Wildlife monitor the amount of sardines landed and collect biological samples from the catch. From 1999 to 2003, each state collected a minimum of three samples per week of at least 25 fish. Because vessels from each state fish in nearly the same location (the fishery operates primarily at the Northern Oregon/Southern Washington state boundary), the two state agencies began a cooperative sampling program in 2004. Each state presently collects three samples per week on alternate weeks during the main fishing period. In addition to collecting biological data on each fish (weight, standard length, sex, and maturity stage), otoliths were extracted and ages were determined by the California Department of Fish and Game. Summary data of Oregon sardine commercial harvest are more fully described in McCrae (2004).

Ichthyoplankton Distribution

The National Marine Fisheries Service (NMFS) conducted an **Ichthyoplankton Survey** off the coast of Oregon and Washington for five years (1994–98). A similar grid of stations was sampled every July, except in 1996 when sampling occurred during June (fig. 1). The sampling was done by vertical tow with a CalVET net (Smith et al. 1985) to a maximum depth of 70 m (Bentley et al. 1996).

Juvenile/Adult Distribution and Size

To describe juvenile/adult sardine distributions, we used catch data from four different fish surveys, which are more fully described in Emmett and Brodeur (2000). The distribution of sampling efforts was mostly at predetermined locations over a number of years. While none of these surveys specifically targeted sardines, sardines were commonly captured.

The first set of surveys, the summertime (July through September) NMFS west coast triennial bottom trawl surveys (**Triennial Survey**), began in 1977. Because the trawls targeted near-bottom species, any sardines captured were likely to have been incidentally caught in mid-water during net deployment and retrieval. We examined catches only from the U.S.-Canada border south to 41.5°N, although many sardines were also caught outside this region (fig. 1). Sardines were counted, measured and weighed, and abundance was calculated using area-swept methodology.[1]

Since 1998, NMFS has conducted three surface trawl surveys of pelagic fish resources off the Northwest: 1) the Bonneville Power Administration (BPA) Columbia River **Plume Survey**, 2) the U.S. Global Ocean Ecosystem Dynamics–Northeast Pacific **(GLOBEC) Survey**, and 3) the **Predator Survey**. During the summer and fall of 1998–2004, the Plume Survey conducted surface surveys for juvenile salmon and associated species along eleven transects off the Washington and Oregon coasts

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[1] M. Wilkins, NOAA, NMFS, AFSC, 7600 Sand Pt Way NE, Seattle, WA, pers. comm.

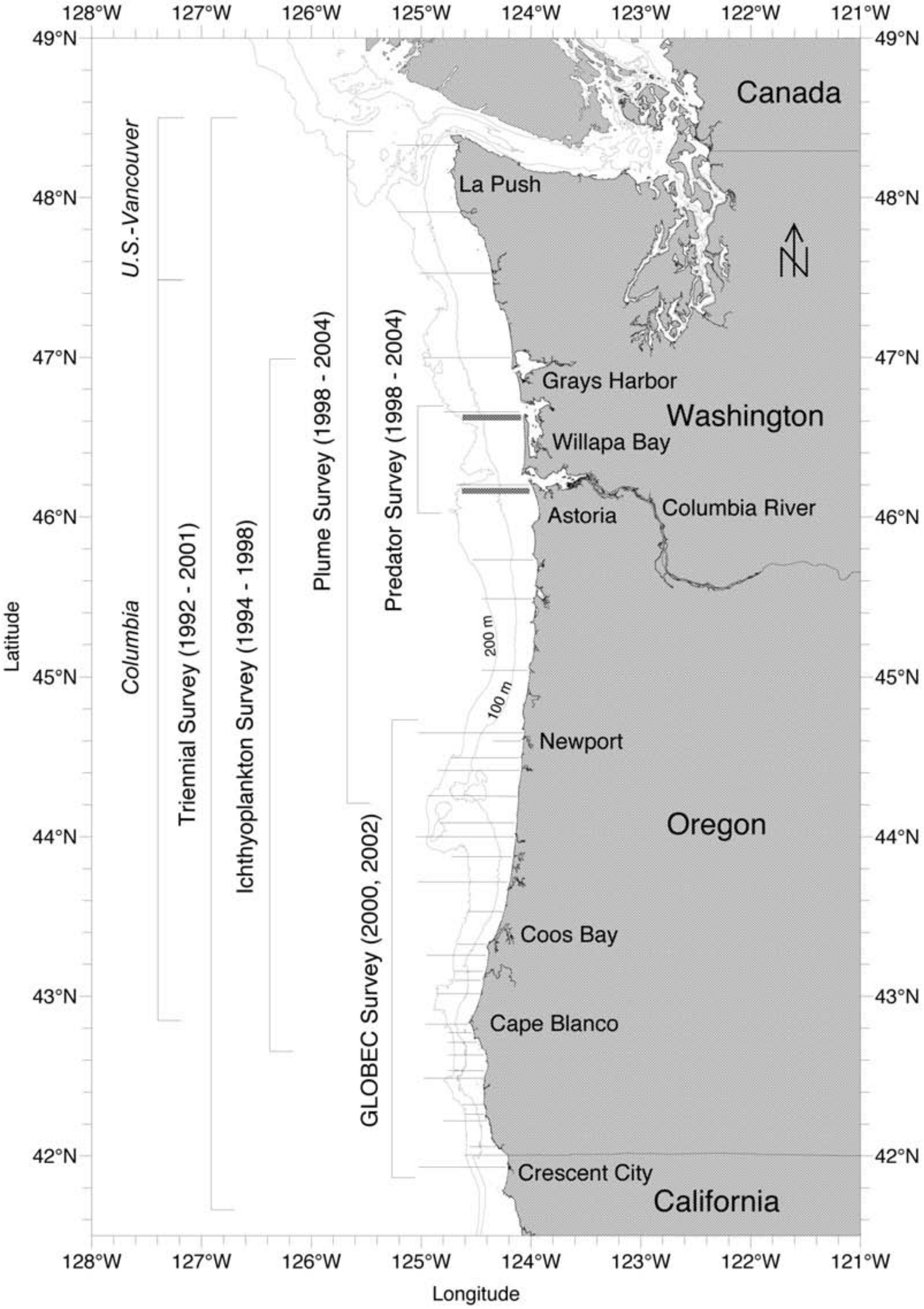

Figure 1. Location of five survey areas where Pacific sardines (*Sardinops sagax*) were collected. Also shown are 100 and 200 m depth contours. Horizontal lines are transects sampled by the Plume and GLOBEC Surveys. Grey rectangles are two transects sampled by the Predator Survey. Columbia and U.S.-Vancouver regions are designated fishery management areas.

(fig. 1; Emmett and Brodeur 2000). Sampling was conducted generally in late May, June, and September of each year with an additional cruise in November 2003. The GLOBEC Survey sampled during June, and August of 2000 and 2002 and extended from Newport, Oregon to Crescent City in northern California. GLOBEC collections were made along predetermined transects but additional opportunistic samplings were made at various stations that showed unique oceanographic signals (Brodeur et al. 2004).

All Plume and GLOBEC Survey sampling was during the day or crepuscular periods. Fish were sampled using a Nordic 264 rope trawl (NET Systems[2], Bainbridge Island, WA) fished directly astern the vessel at the surface. The trawl has an effective fishing mouth of 12 m deep and 28 m wide (336 m^2) as identified during an early cruise (June 2000) using net mensuration equipment (Emmett et al. 2004). The mouth was spread apart by a pair of 3.0 m foam-filled trawl doors. The trawl was towed with about 300 m of warp for 30 min at 1.5 m sec^{-1}. To fish the trawl at the surface, a cluster of two meshed A-4 Polyform buoys were tethered to each wing tip, and two single A-4 Polyform floats were clipped on either side of the center of the headrope. Mesh sizes ranged from 162.6 cm in the throat of the trawl near the jib lines to 8.9 cm in the cod end. To maintain catches of small fish and squids, a 6.1 m long, 0.8 cm knotless liner was sewn into the cod end.

The Predator Survey consisted of a series of biweekly cruises on two transects near the Columbia River mouth in spring and summer of 1998–2004 (fig. 1; Emmett et al. 2001). Sampling was conducted at night using the same surface trawl gear as in the Plume and GLOBEC Surveys.

Sardines captured in trawls were counted and up to 50 of them were measured to fork length (FL) (mm). However, when there were very large catches a subsample of sardines was measured, counted, and weighed; remaining sardines were mass weighed. Total number of sardines in the haul was then calculated using the known number of sardines/kg. Sardine density was calculated by multiplying the number of sardines in a haul by the volume of water the net fished, which was standardized to number per 10^6 m^3. The volume of water fished was calculated as the trawling distance multiplied by the effective fishing mouth area (336 m^2).

Habitat Analysis

We were interested in determining if any environmental factors were related to the distributions of sardine egg, larval, juvenile, and adult stages. During Ichthyoplankton, Plume, and GLOBEC Surveys, temperature (°C; T) and salinity (S) measurements were collected at 3 m depths from each station using a Sea-Bird SBE 19 SeaCat conductivity, temperature, and depth (CTD) profiler. In-vitro chlorophyll *a* (µg/l; C) was measured by filtering water samples collected from 3 m depth, and then examining the filtrate concentrations spectrophotometrically (1994–96) and fluorometrically (1996–98). During GLOBEC Surveys, neuston biovolumes were identified from settled plankton volumes collected from a 1 m × 0.3 m neuston net. The neuston net had 0.333 mm mesh and was set out 60 m beyond the vessel's wake and towed at 3 km hr^{-1} for 5 min.

A General Linear Model (GLM) was used to investigate the relationship between average sardine densities during Predator Survey cruises and average 3 m depth temperatures and salinities. Sardine densities were $\log_{10}(x+1)$-transformed before analysis.

We explored the relationships between environmental factors and sardine densities (by life stages and size classes) using General Additive Models (GAM) (Hastie and Tibshirani 1990). We chose this nonparametric method due to the high number of zero catches and the nonlinear relationships between sardine densities (all life stages) and environmental variables.

A Gaussian error model was used in the GAM analysis, with a link identity function based on the following model (Bigelow et al. 1999):

$$\ln(\text{density} + 0.01) =$$
$$a + \text{lo}(T) + \text{lo}(S) + \text{lo}[\ln(C+1)] + e$$

where a is a constant, e is the error term and lo(x) is the loess-smoothed independent variable. GAMs were implemented using the mgcv library of R (Wood 2001).

Food Habits

Analyses of sardine diets were synthesized from two studies: the September 1999 Plume Survey and the August 2000 and June and August 2002 GLOBEC Surveys. In both studies, sardines collected for stomach analysis were frozen whole onboard the ship (−20°C), transported to the lab, measured [fork lengths (FL), mm], and weighed (g); then their stomachs were removed and preserved in 10% buffered formalin for a minimum of 10d.

Contents of the cardiac stomach region were identified to the lowest taxonomic level possible, enumerated, and wet weighed (g). Stomach contents in the pyloric stomach region were too digested to identify; therefore, they were not included in laboratory analysis. Stomachs frequently consisted of phytoplankton and microzooplankton too numerous and small to count efficiently. For these stomachs, prey >1.0 mm were removed, identified, measured for length, and wet weighed, and the remaining contents subsampled. To accomplish subsampling, stomach contents were first measured for total settled volume in a volumetric flask, then resuspended and subsampled with a 5.0 ml Hensen-Stempel pipette. Settled volume of the subsample was then measured and examined for prey identification and enumeration. Wet weight of specimens in the flask was calculated from length-weight relationships previously identified for individual prey. The subsample of prey counts and weights was projected to estimate the entire contents of the

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[2] Reference to trade name does not mean endorsement by NOAA, National Marine Fisheries Service.

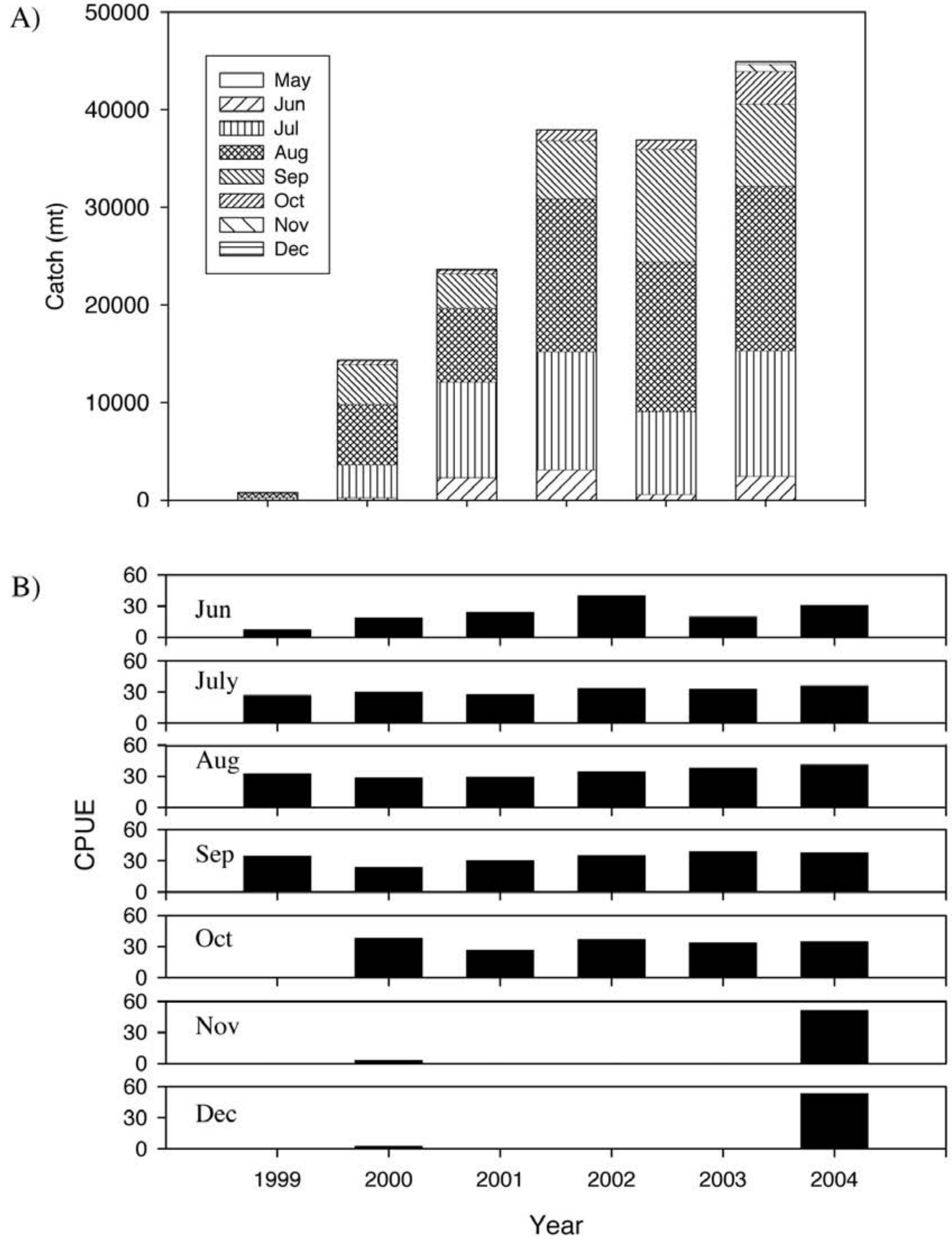

Figure 2. Monthly annual (A) commercial landings and (B) catch per unit effort (CPUE, mt/fishing trip) of Pacific sardine (*Sardinops sagax*) off Oregon/Washington, 1999–2004.

stomach by the multiplier derived from the ratio of subsample/stomach total settled volume. Finally, prey >1.0 mm were added to this estimate to give the full diet for that fish. Stomach fullness was defined as the percentage of total stomach prey weight divided by sardine body weight.

Linear regression was used to identify the relationships between stomach fullness, neuston biovolumes, and chlorophyll-*a* concentrations. Stomach fullness was arcsine-transformed and both neuston biovolumes and chlorophyll-*a* concentrations were log-transformed before linear regression analysis. A *t*-test was used to

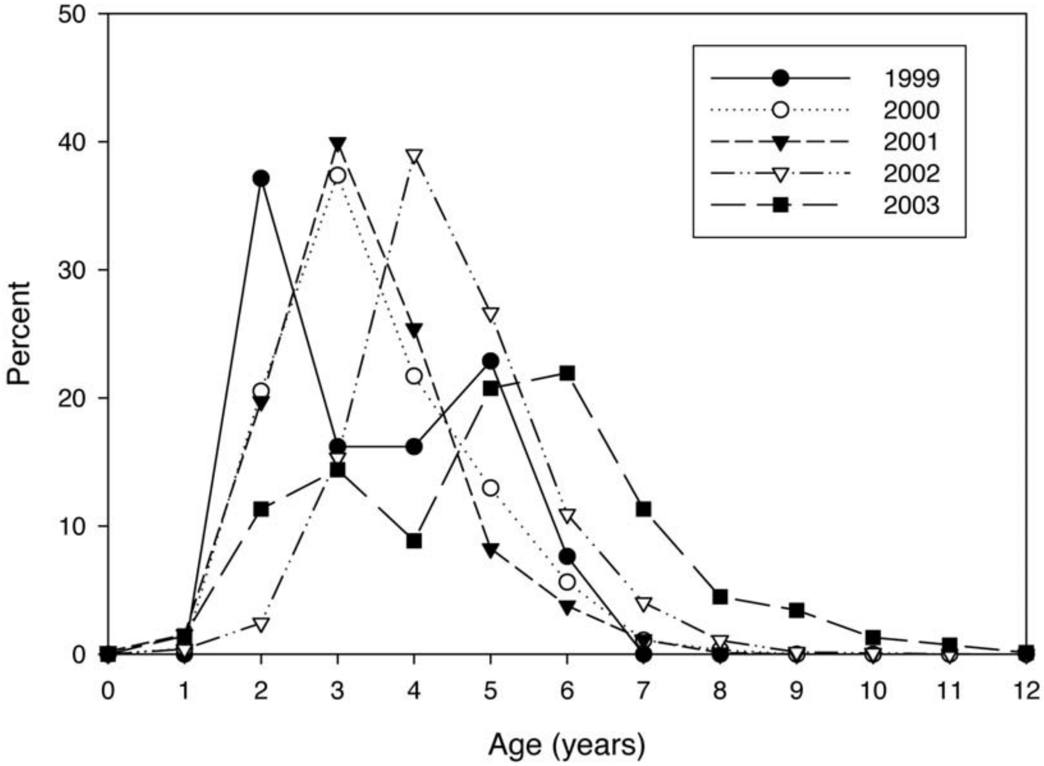

Figure 3. Age distribution of commercially landed Pacific sardine (*Sardinops sagax*) off Oregon/Washington, 1999–2003.

identify differences in stomach fullness between day- and night-caught sardines and to identify differences between nearshore- (<150 m isobath) and offshore- (>150 m isobath) caught sardines.

Identification of Sardine Predators

Sardine fish predators were identified from stomachs collected from the Predator, Plume and GLOBEC Surveys. Most of the fish stomachs examined from the Plume study were from sharks and juvenile and adult salmonids. Predator Surveys provided stomachs from Pacific hake (*Merluccius productus*), jack mackerel (*Trachurus symmetricus*), and chub mackerel (*Scomber japonicus*). The first 30 stomachs were taken from each predator species from each haul during the Predatory study (Emmett et al. 2001). The GLOBEC Survey provided stomach data from more than 20 species of fish and squids, including forage fishes and large sharks.[3] For most of these collections, whole frozen fish were brought back to the laboratory for detailed analysis, although shipboard scans of stomachs were performed on large fishes. Some shark stomach contents were collected by flushing out the contents using a pump, and the sharks were released alive. Overall, 10,000 fish stomachs were examined to identify which species consumed sardine.

RESULTS

Commercial Catch and Age Distribution

Recent commercial landings of sardines in the Pacific Northwest started in 1999 when 1,000 mt were landed. By 2004, almost 45,000 mt were landed (fig. 2a), mostly in Astoria, Oregon. Landings generally begin in June and peak in August (fig. 2), with no landings from November through May. However, this seasonal harvest pattern can fluctuate, as some landings continued into December of 2000 and 2004 (fig. 2a). Catch per unit effort (CPUE) averaged between 25 to 36 mt/trip during June through September (fig. 2b), with highest average CPUE occurring in 2004. The unusually calm weather during fall and early winter 2004 allowed a few very successful fishing trips (fig. 2b).

Commercially harvested sardines range from 1 to 12 years old, with the majority being 3 to 5 years old (fig. 3). In most years (1999–2002), the catch has been primarily 2- to 5-year-old fish. However, in 2003 the catch was composed largely of older fish (i.e., 5- and 6-year-olds).

Ichthyoplankton Survey

For the entire five-year Ichthyoplankton Survey period, sardine eggs and larvae were the dominant taxon collected, comprising 26.5% of all ichthyoplankton collected. Sardine abundance exceeded that of the next two

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[3] T. Miller, unpubl. data

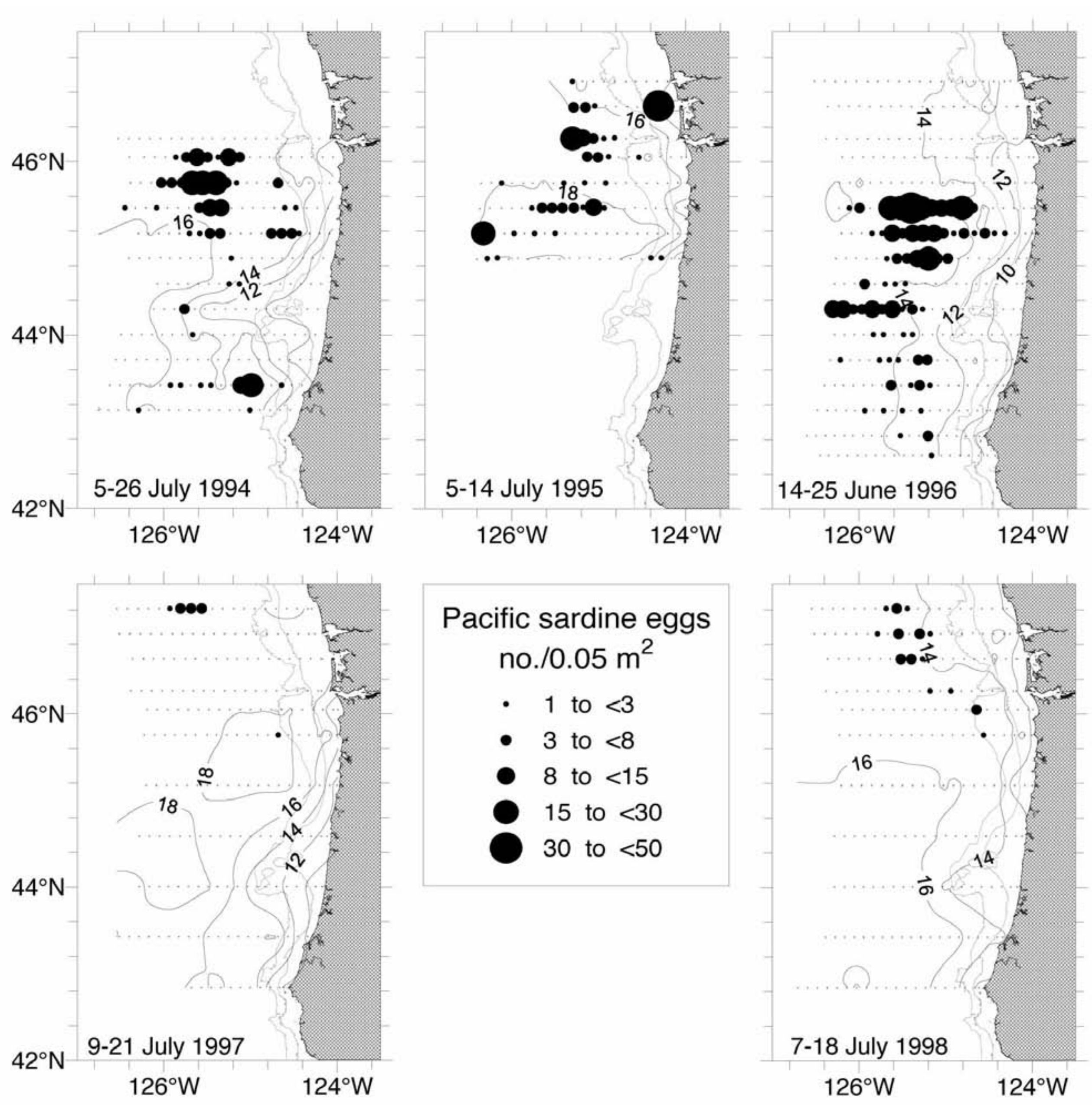


Figure 4. Distribution of Pacific sardine (*Sardinops sagax*) eggs during NMFS ichthyoplankton surveys off Oregon/Washington, 1994–98. Also shown are 3 m depth isotherms and 100 and 200 m depth contours.

species (*Diaphus theta* and *Stenobrachius leucopsarus*) combined. Sardine eggs were distributed over a substantial latitudinal proportion of the study area and well offshore (fig. 4). In some years (e.g., 1995) the entire spawning distribution was probably not effectively sampled because the spawning area went beyond the survey area. Nevertheless, sardine eggs were generally distributed between the 14° and 16°C isotherms (fig. 4). The distribution of sardine larvae was similar to that of eggs, although larvae were slightly farther offshore in most cases (fig. 5).

Triennial Surveys: Juvenile and Adult Spatial Distribution, Abundance, and Size

Sardines were not caught in any of the Triennial Surveys until 1992 (the surveys began in 1977), when high numbers were caught off the Columbia River (fig. 6). During all subsequent surveys, sardines were mainly distributed over the middle- and outer-shelf regions. In 1995, sardines were widely distributed spatially, occurring both farther south and more inshore compared to 1992, although overall abundance was lower. In 1998, catches were again lower and occurred predominantly

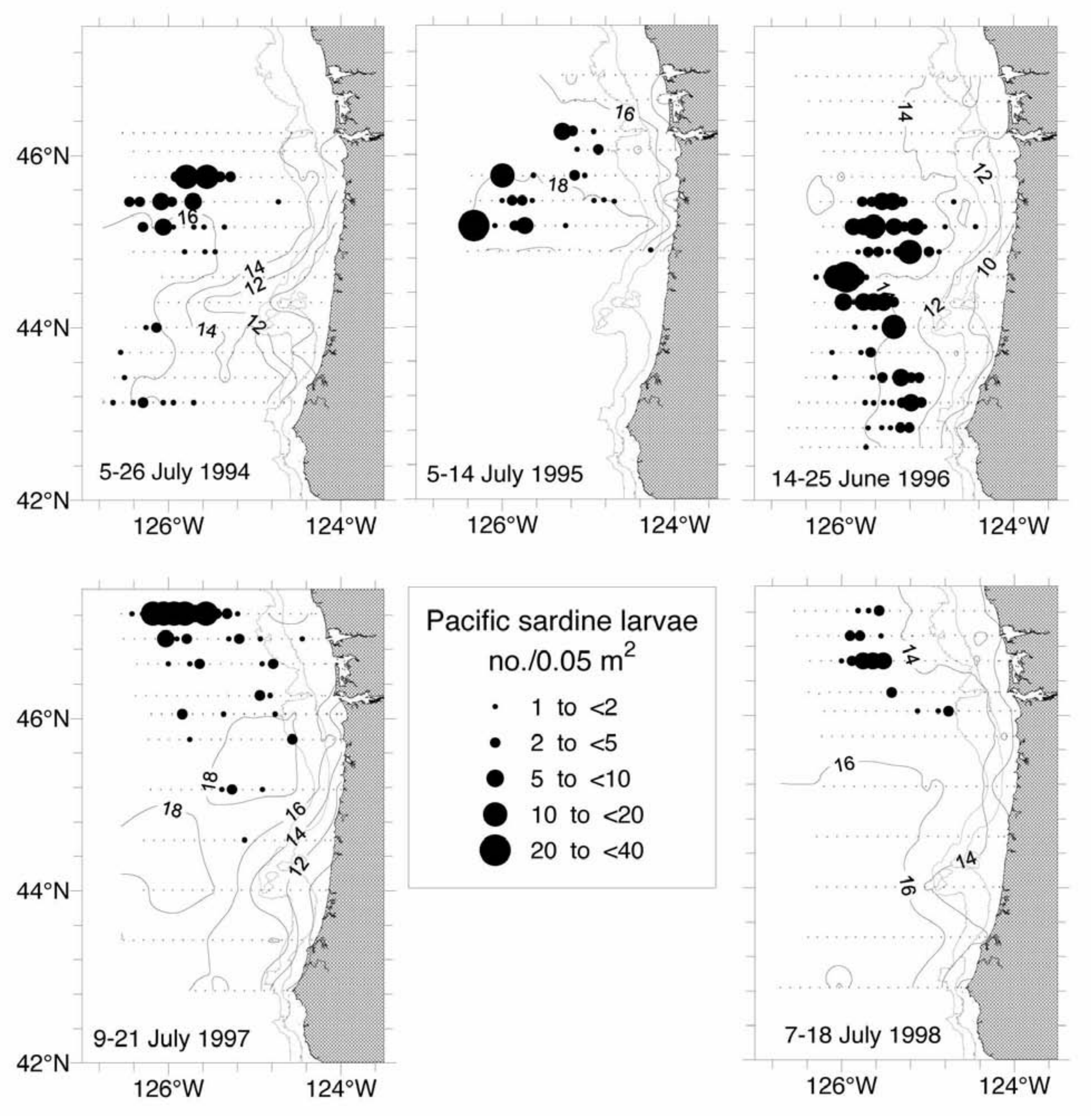


Figure 5. Distribution of Pacific sardine (*Sardinops sagax*) larvae during NMFS ichthyoplankton surveys off Oregon/Washington, 1994–98. Also shown are 3 m depth isotherms and 100 and 200 m depth contours.

in the vicinity of the Columbia River. In 2001, sardines were more common north and south of the Columbia River mouth (fig. 6). Sardine biomass estimates from these bottom trawl surveys showed a decline in biomass in both the U.S.-Vancouver and Columbia statistical regions from 1992 to 1998 with an increase in 2001 (fig. 7). However, bottom-trawl catches are not efficient estimators of sardine abundance.

Sardines caught during the 1998 Triennial Survey ranged from 120 to 280 mm (FL) (fig. 8). Several size classes were represented in 1998, and sardines were progressively larger from south to north. There was also a second smaller-sized group, probably primarily 1-year-olds, off northern Washington—evidence that successful spawning and recruitment had probably occurred off the Northwest in 1997 (fig. 8).

NMFS Surface-Trawl Surveys: Length Frequencies

Fork lengths of sardines captured during the various NMFS surface-trawl surveys ranged from 40 to 368 mm (mean = 158 mm) for all data combined from

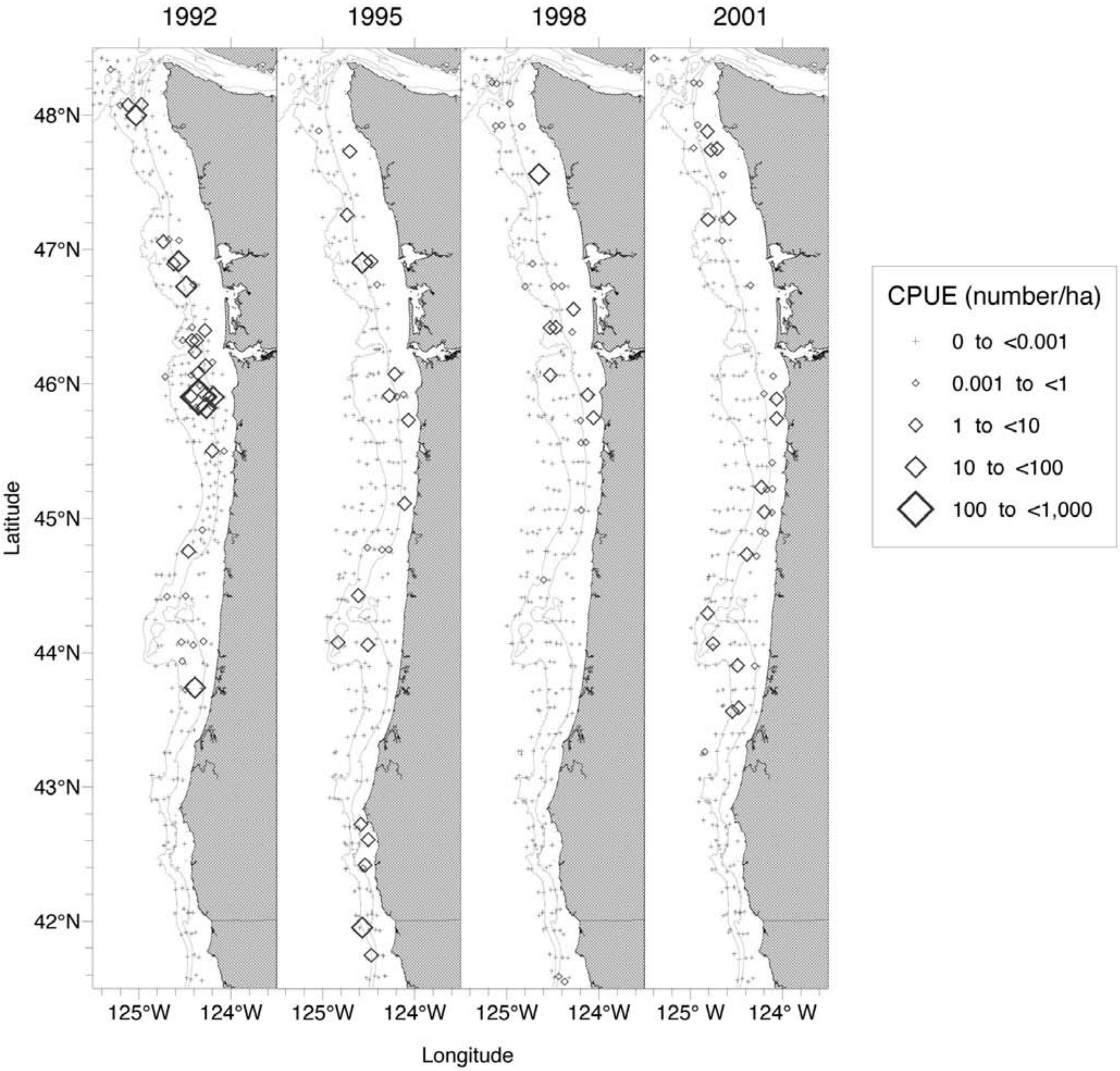


Figure 6. Distribution of Pacific sardine (*Sardinops sagax*) during NMFS 1992, 1995, 1998, and 2001 Triennial Surveys off Oregon/Washington. Also shown are 100 m and 200 m depth contours.

1998 to 2004. Analysis of length frequencies indicated that three size classes of sardines were caught, particularly in September (fig. 9). Length-frequency data from Plume Surveys in September indicate large annual fluctuations in the sizes of sardines inhabiting the PNW coast from 1998 to 2004 (fig. 10). While one or two large size classes are present each year, the small size class (<110 mm FL) is not. These small sardines appear to represent 0-age sardines, those spawned off Oregon and Washington in the summer. They were sparsely present in 1998 and 2001 but strongly represented in 2003 and 2004, years when the ocean was warm. Further analysis, along with considerations of growth and mortality, led us to assign sardines to size classes using lengths by calendar month (tab. 1). Small-, medium-, and large-sized groups were used to examine the spatial distribution of sardine catches and for statistical analysis. Sardines often show a large variance in age versus length (Butler et al. 1996). While we are confident that the small (<110 mm FL) sardines captured in September are 0-age, we are uncertain about the ages of other size classes.

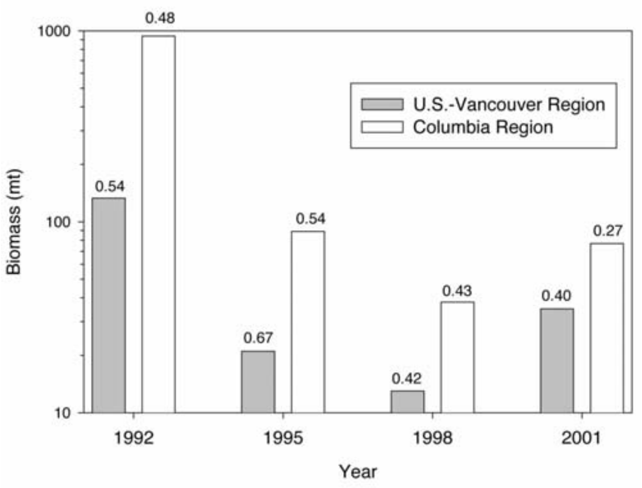


Figure 7. Estimated minimum biomass of Pacific sardine (*Sardinops sagax*) in the U.S.-Vancouver and Columbia fishery management regions from NMFS Triennial Surveys. Numbers above bars are the coefficient of variation of the biomass. Biomass estimates are considered minimums, since the trawl was mainly on the bottom and would not have sampled the sardines effectively.

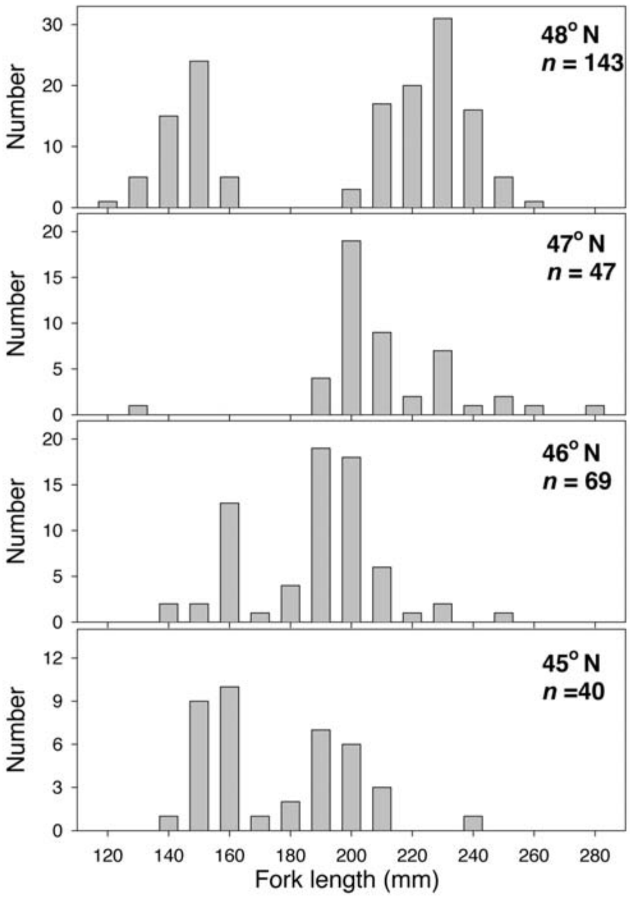


Figure 8. Size distribution of Pacific sardine (*Sardinops sagax*) collected during the NMFS 1998 Triennial Survey by degree of latitude.

Plume and GLOBEC Surveys: Juvenile and Adult Spatial Distribution and Abundance

Juvenile and adult sardines collected during Plume and GLOBEC Surveys showed substantial interannual and seasonal variation in distribution and abundance (fig. 11). During May, when sampling frequency was low, Pacific sardines were caught at only one station in 1999, 2001, and 2002, four stations in 2003, and eight stations in 2004; no sardines were caught in 2000 (fig. 11a). The large catches in May 2004 were primarily medium-sized sardines (fig. 11a). In June 1998, both medium- and large-sized sardines were collected, although at low frequencies. In June 1999, 2000, and 2001, sardines caught were primarily large-sized (fig. 11b) but still relatively uncommon. In 2002, catches of large-sized sardines were common, but only two stations had densities >1,000 10^{-6} m^{-3}. In June 2004, medium-sized (≤160 mm FL) sardines were caught at high densities at most stations (fig. 11b).

In August of 2000 and 2002, mostly large-sized (>180 mm FL) sardines were captured; while densities were generally low, a few hauls captured large numbers. A few sardines were also captured beyond the shelf break at the end of transects (fig. 11c).

During September 1998, sardines were collected at less than half the stations as in September 2003 (fig. 11d). Several stations in September 1999 and 2000 had high densities of both medium- and large-sized sardines. In 2001 small-sized, or 0-age sardines, were caught only along the two southernmost transects; in 2002 they were found at two stations in low abundance. However, in 2003 and 2004 small sardines had high densities at several stations (fig. 11d). In September 2003, most small sardines were caught at offshore stations along three transects, but in September 2004, their spatial distribution was more widespread (fig. 11d). The small juveniles had a more offshore distribution than sardines in the medium-sized group, which showed highest densities within the 100 m isobath (fig. 11d).

In November 2003, many juvenile sardines were caught along the Columbia River transect (46.2°N) and toward the end of other transects sampled (fig. 11c). Similar to September 2003, no medium-sized sardines and only a few large-sized sardines were caught.

Predator Surveys: Juvenile and Adult Abundance

Sardine densities around the mouth of the Columbia River showed very large monthly and annual fluctuations (fig. 12). Only in 1998, a warm El Niño year, were May sardine densities relatively high. Highest average monthly densities generally occurred in July, but not all years. The highest catch density was 2,337 10^{-6} m^{-3} (July 2003), and the lowest densities (zero catch) were in May 1999 and 2000.

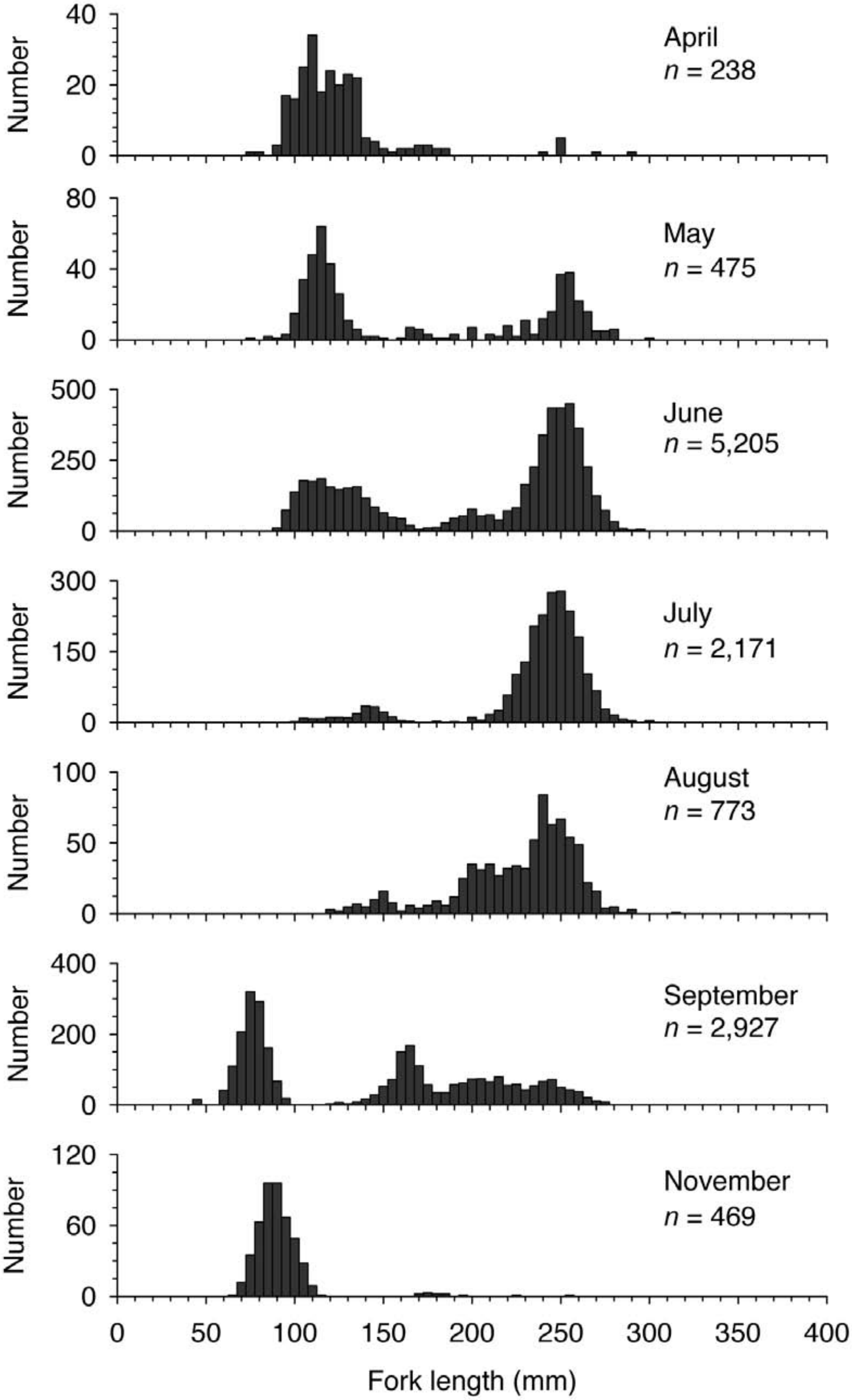


Figure 9. Monthly length-frequency distribution of Pacific sardine (*Sardinops sagax*) collected during all NMFS 1998–2004 surface trawl surveys.

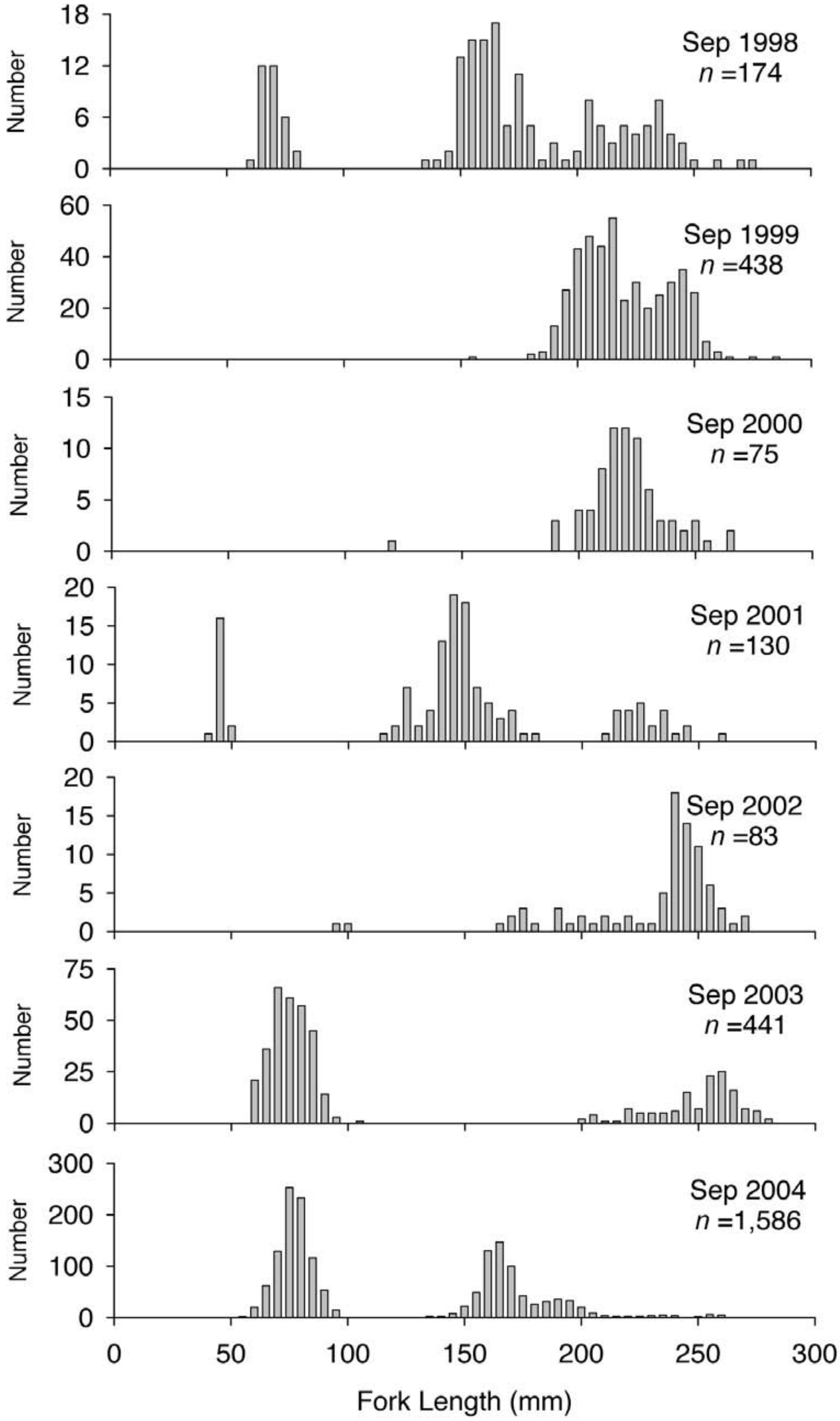


Figure 10. Length-frequency distribution of Pacific sardine (*Sardinops sagax*) captured during September Plume Surveys off Oregon/Washington, 1998–2004.

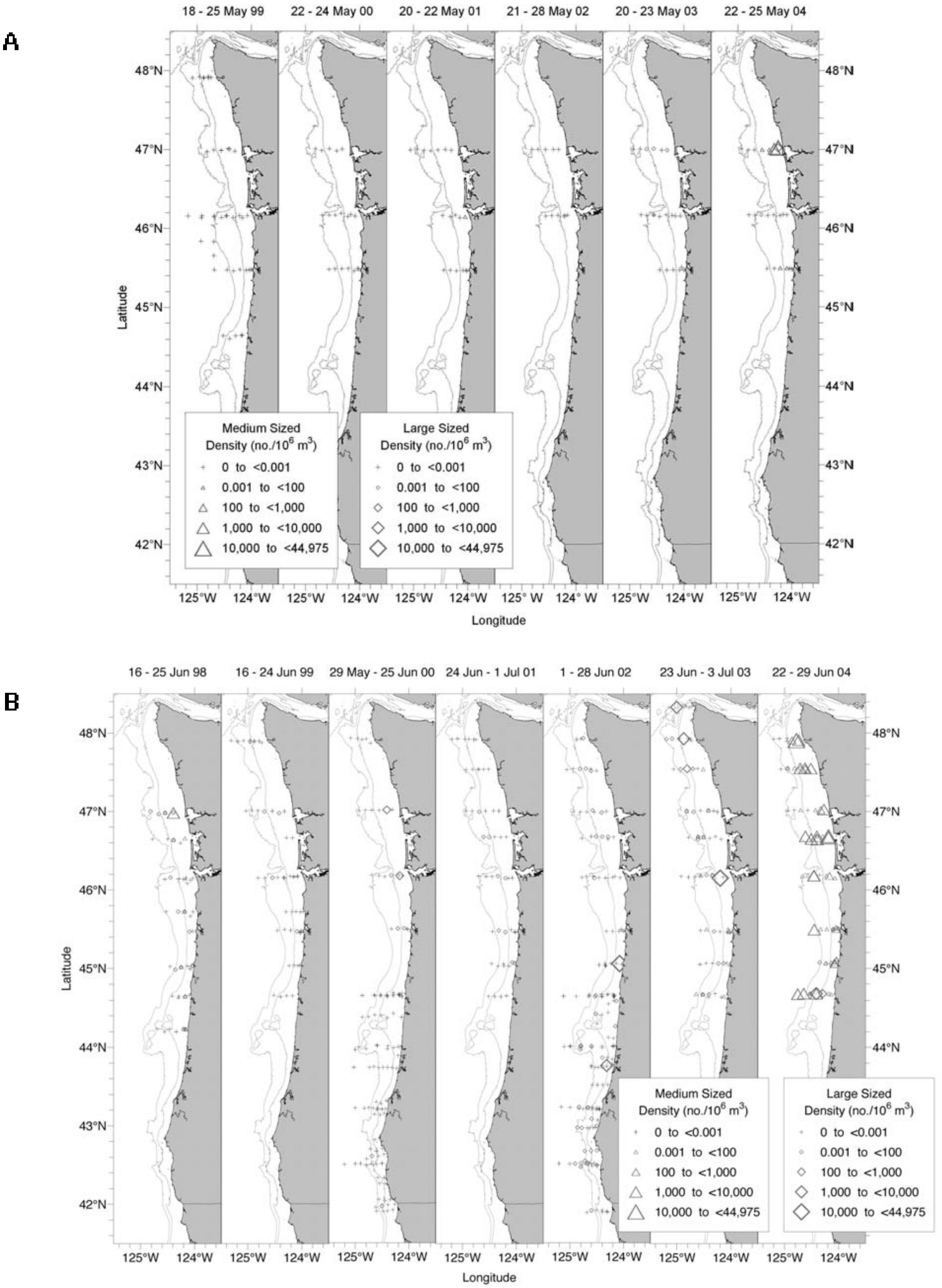


Figure 11. Distribution of Pacific sardine (*Sardinops sagax*) from NMFS 1998–2004 GLOBEC and Plume Surveys off Oregon and Washington during May (A), and June (B). The + signs indicate locations of a surface trawl. Also shown are 100 and 200 m depth contours.

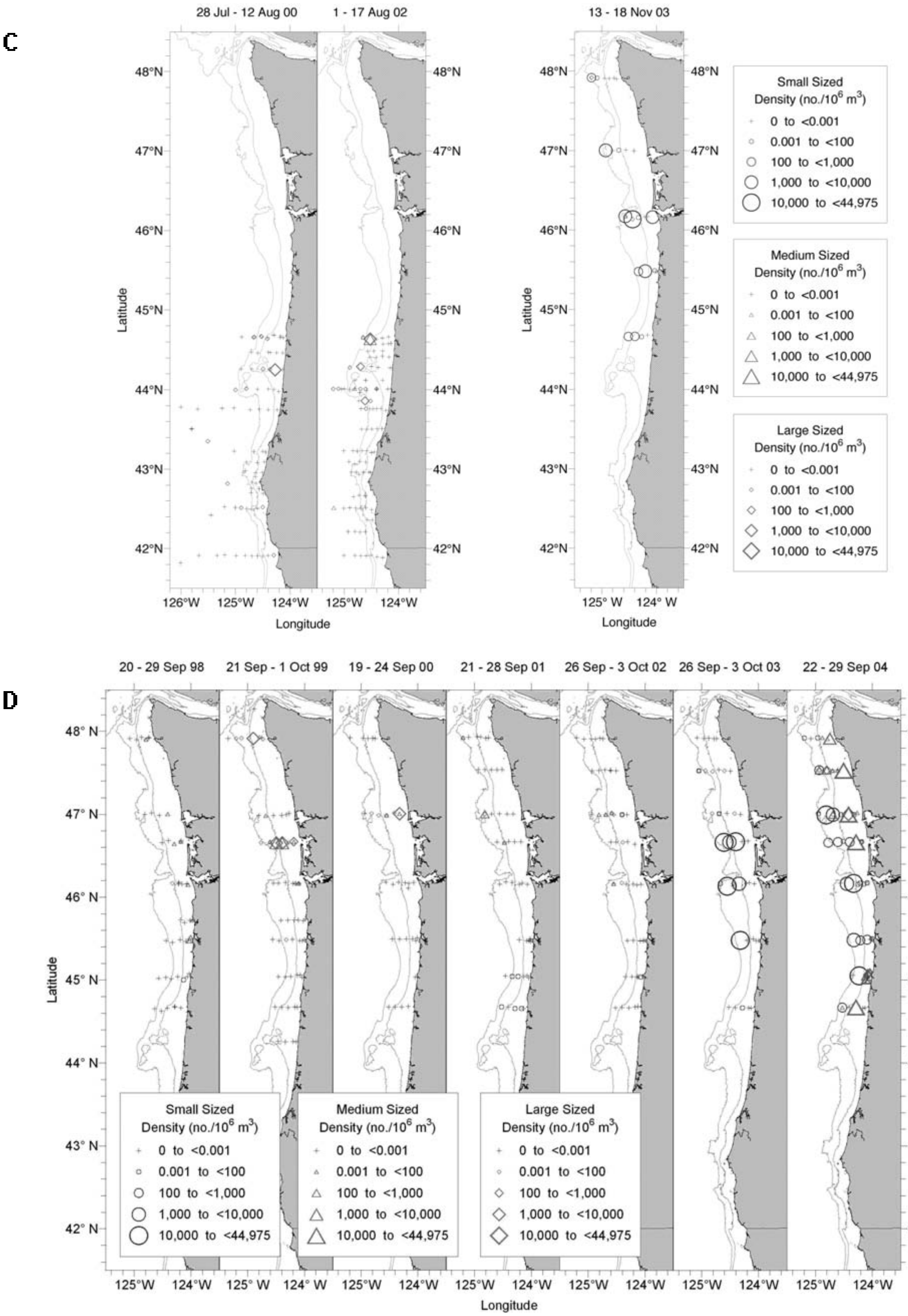


Figure 11. Distribution of Pacific sardine (*Sardinops sagax*) from NMFS 1998–2004 GLOBEC and Plume Surveys off Oregon and Washington during August and November (C), and September (D). Also shown are 100 and 200 m depth contours.

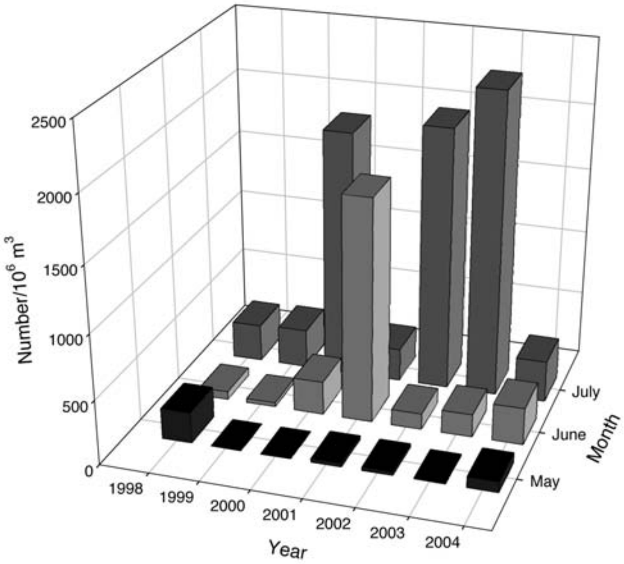


Figure 12. Average monthly densities of Pacific sardine (*Sardinops sagax*) during 1998–2004 NMFS Predator Surveys off the mouth of the Columbia River.

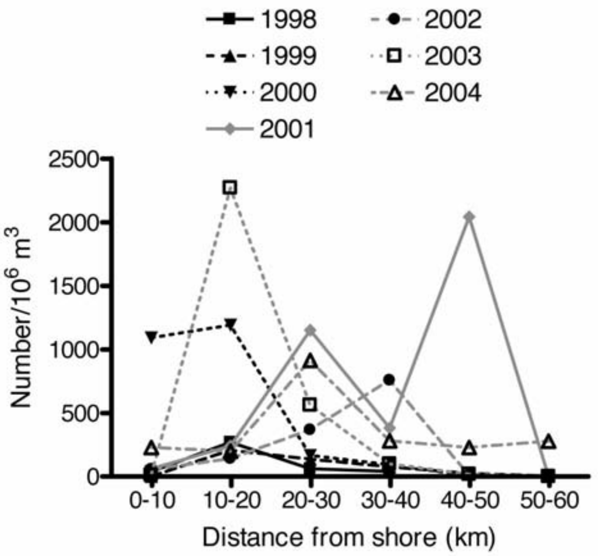


Figure 13. Average annual density of Pacific sardine (*Sardinops sagax*) at different distances from shore during 1998–2004 NMFS Predator Surveys off the mouth of the Columbia River.

TABLE 1
Fork lengths (mm) of Pacific sardines (*Sardinops sagax*) used to discriminate size classes of sardines

Month	Small	Medium	Large
April		≤150	>150
May		≤155	>155
June		≤160	>160
July		≤170	>170
August		≤180	>180
September	<110	110 ≤ x ≤ 195	>195
October	<120	120 ≤ x ≤ 205	>205
November	<130	130 ≤ x ≤ 215	>215

TABLE 2
Results of General Additive Modeling (GAM) analysis of the effects of temperature (°C; Temp), salinity (psu; Sal), and chlorophyll *a* concentrations (µg/l; Chl) on various life stages of Pacific sardine (*Sardinops sagax*). Shown are the probability values for the full GAM model for each variable and all significant *p* values < 0.05 are in boldface type. The sample size is the number of cases where all three environmental variables were measured

		Variable		
Life Stage	Sample size	Temp	Sal	Chl
eggs	744	**0.0338**	0.1429	0.0617
larvae	744	0.7006	0.4956	0.7320
small juveniles	972	**0.0370**	0.2200	**0.0139**
medium juveniles/adults	972	**0.0416**	0.1728	**0.0119**
large adults	972	0.4231	**0.0358**	**<0.0001**

Sardine densities showed little relationship with distance from shore (fig. 13). While in some years the highest average catches were nearshore (<20 km, 2000 and 2003), in other years, the highest catches were offshore (40–50 km, 2001).

Habitat Analysis

Using all data from the NMFS surface-trawl surveys, we found that large- and medium-sized sardines were more frequently captured at lower surface salinities and temperatures than small-sized sardines (fig. 14). Small-sized sardines were most commonly found in warmer temperatures (>12°C) and higher salinities (>28).

For the Ichthyoplankton, Plume, and GLOBEC Surveys, the GAM three-factor models revealed that temperature was significantly related to the abundance of eggs and small- and medium-sized life history stages (tab. 2). The relationship between catch and temperature was positive for all stages. Salinity was a significant indicator for only the large-sized sardines and showed a negative effect. Chlorophyll *a* was an important explanatory variable only for the juvenile and adult stages (tab. 2) and showed a positive coefficient with all three life stages.

Sardine densities from the Predator Survey were highly related to temperature; most fish were caught when the 3 m depth temperature was >12°C (fig. 15). Few sardines were caught at <12°C. The average temperature at 3 m depth explained 50% of the variation (adjusted R^2) (GLM, $p < 0.01$) in average sardine densities per cruise off the Columbia River from 1999 to 2004.

Food Habits

Sardines consumed a variety of prey depending on location and season. In September 1999, sardines off Washington had diets composed primarily of phytoplankton; 84% by weight (tab. 3). Copepods (all stages) and Appendicularia were the primary animal prey items

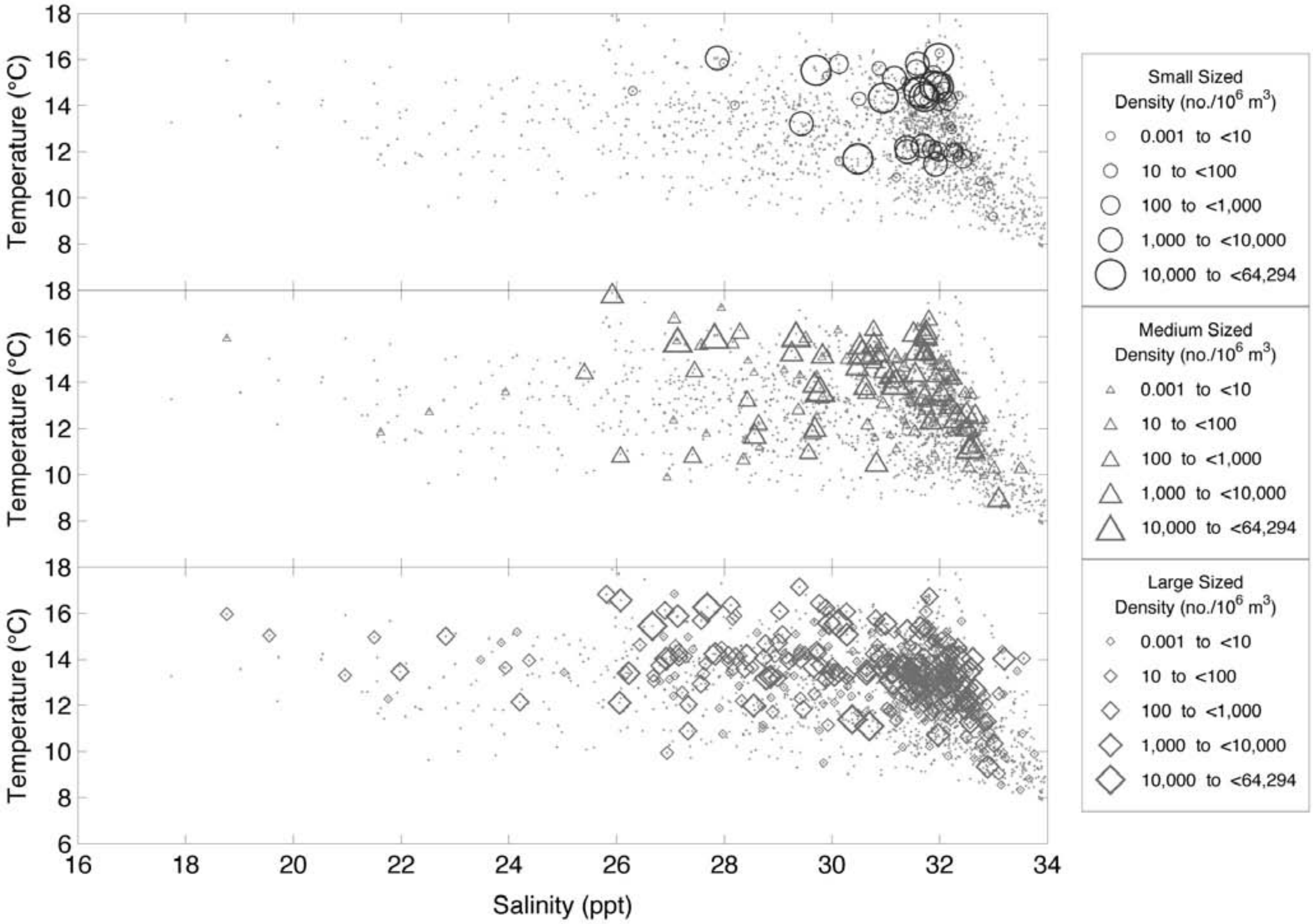


Figure 14. Densities of three different size classes of Pacific sardine (*Sardinops sagax*) captured during GLOBEC and Plume Surveys in relation to 3 m depth ocean temperatures and salinities. Locations where no sardines were caught are shown as light grey dots. Refer to Table 1 for size class definitions.

(tab. 3). Identifiable copepods in the stomachs were primarily *Acartia* spp. and *Pseudocalanus* spp.

Numerically, adult copepods dominated the diet in August 2000 and June and August 2002, (tab. 3), while euphausiids and copepods were primary prey by wet weight. *Euphausia pacifica* was the most important prey by weight during August 2000, whereas *Thysanoessa spinifera* was the primary prey in August 2002. Most copepods consumed in 2000 and 2002 were at egg, nauplii, or copepodite stages.

Analysis of stomach fullness from sardines collected during the day and night indicated no diel feeding differences (*t*-test, $p = 0.54$). All stomachs were full or distended and had an average stomach fullness of 0.44%±1.23% (SD) of sardine body weight. Stomach fullness was poorly related with neuston biovolume (linear regression, $p = 0.51$). There was also no relationship between phytoplankton abundance in the diet (percent wet weight) and chlorophyll *a* concentrations (linear regression, $p = 0.81$).

Analysis of sardines collected during the GLOBEC Survey showed nearshore/offshore differences in feeding. Sardines in nearshore habitats (inshore of the 150 m isobath) fed primarily on phytoplankton and copepods, whereas those in offshore habitats (>150 m isobath) consumed predominantly adult euphausiids (fig. 16). Nearshore sardines had higher stomach fullness than offshore sardines in August 2000 (*t*-test, $p = 0.002$) but not during June or August 2002 (*t*-test, $p > 0.05$).

Sardine diets from September 1999 and August 2002 contained high proportions of phytoplankton, which coincided with high chlorophyll-*a* concentrations during the two periods (11.7±5.0 and 16.3±7.2 $\mu g \cdot l^{-1}$, respectively). The relatively low contribution of phytoplankton to sardine diets in August 2000 and June 2002 coincided with low chlorophyll-*a* concentrations (4.9±4.1 and 3.5±4.1 $\mu g \cdot l^{-1}$, respectively).

Sardine Predators

We identified seven different fish species that had consumed sardines (tab. 4). Predators included both juvenile and adult stages of coho and Chinook salmon, Pacific hake, jack mackerel and three species of shark.

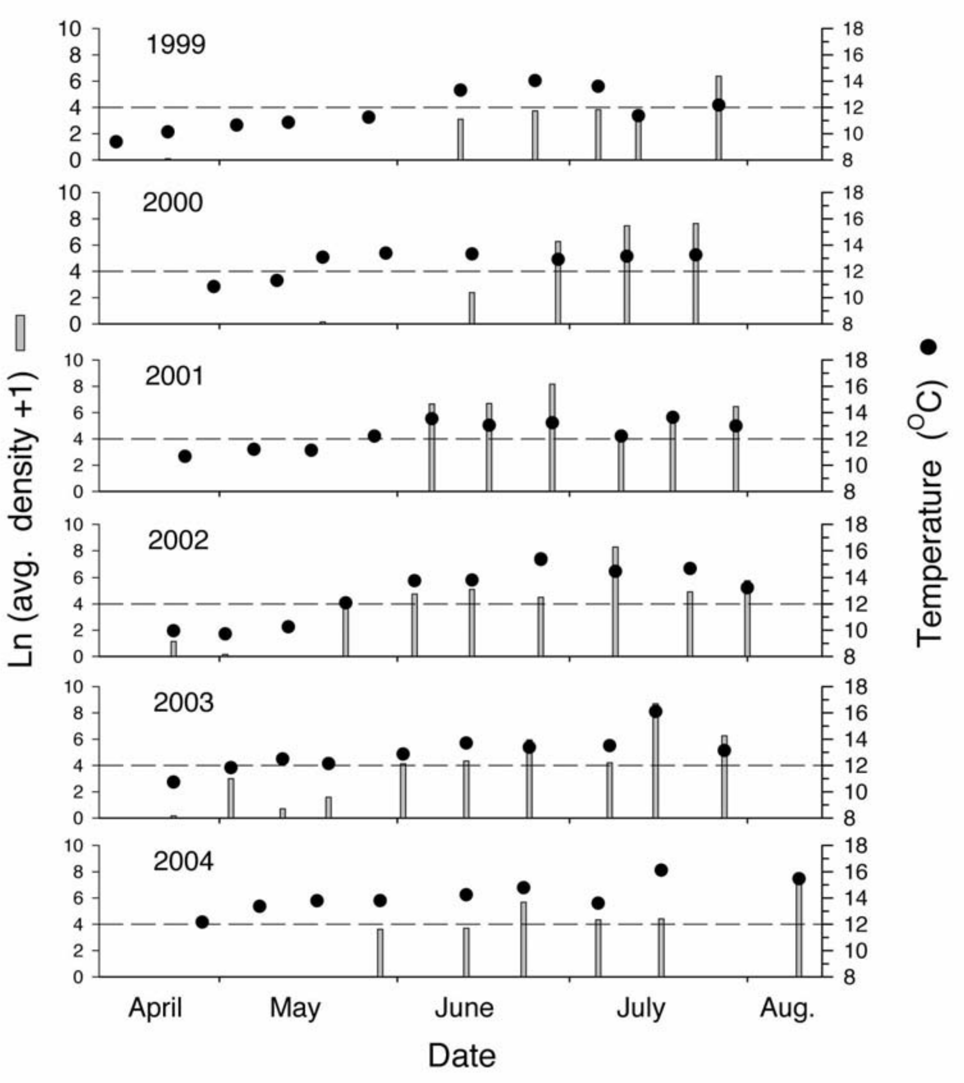


Figure 15. Average cruise densities of Pacific sardine (*Sardinops sagax*) during 1998–2004 NMFS Predator Surveys off the mouth of the Columbia River in relation to average cruise surface (3 m depth) temperatures.

DISCUSSION

Distribution and Stock Structure

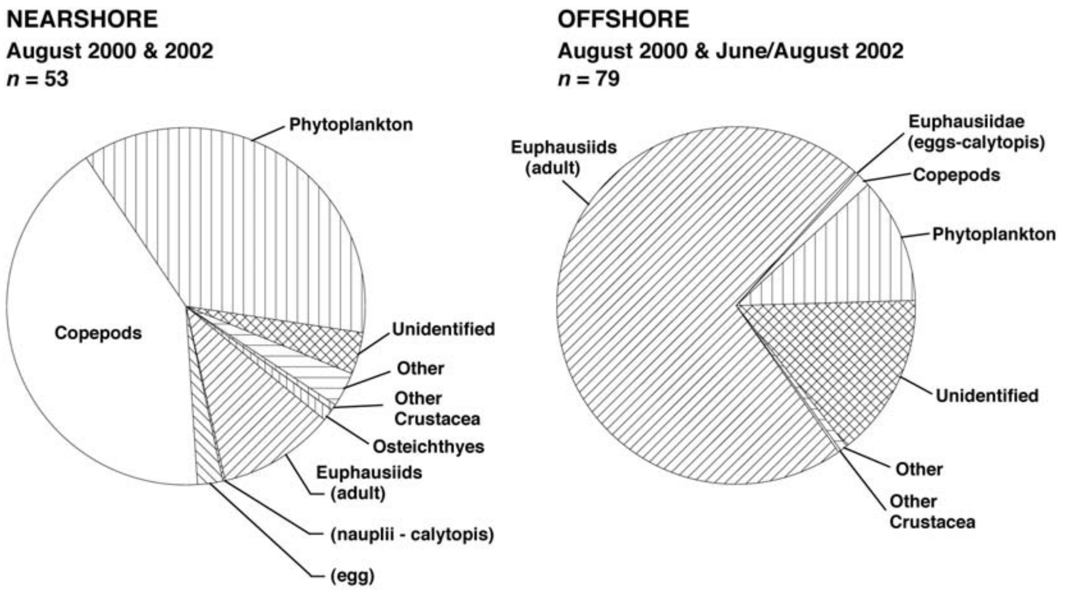
The increase in the commercial sardine catch from 1999 to 2004 off the PNW appears to be related to both more fishing effort and changes in sardine abundance. However, there remains much uncertainty regarding how many sardines reside off the PNW and whether the individuals spawning off Oregon/Washington are a separate population from those that reside in California waters (Smith 2005). If sardines spawning off the PNW (June/July, this study) are not also spawning off California (February–June/July) (Hernandez-Vazquez 1994), then sardines in the PNW may be considered a separate population.

There is presently little information confirming that PNW and California sardines are separate stocks. Radovich (1982), who studied Northwest sardines in the 1930s and 1940s, believed they were separate stocks. However, recent genetic data indicate no identifiable stock differences between PNW and California sardines (Hedgecock et al. 1989; Lacomte et al. 2004), but genetic data may be insensitive to recent population differentiation (Kinsey et al. 1994). The age-class structure of harvested sardines off Oregon/Washington does appear to reflect patterns of local recruitment, suggesting separate stocks. The age-class structure of the commercially caught sardines in the PNW (fig. 3) suggests that many were locally spawned and are possibly a separate population. In 1999, most of the sardines harvested were 2-year-olds (1997-year-class); this year-class was also important in 2000. In 2003, the 1997 year-class was again the primary year-class captured; few younger age-classes were caught. Both 1997 and 1998 were warm years accompanied by successful spawning and recruitment. From 1999 to 2002, the ocean was

TABLE 3
Pacific sardine (*Sardinops sagax*) diets by percent number (%N) and wet weight (%W)

	Time Period							
	1999 September		2000 August		2002 June		2002 August	
Prey Taxa	%N	%W	%N	%W	%N	%W	%N	%W
Chordata								
Osteichthyes egg			<0.1	0.4				
Appendicularia	6.7	2.9	0.2	0.2	0.6	0.3		
Arthropoda								
Crustacea								
Copepoda								
Unidentified egg	42.0	2.3	1.1	<0.1				
Unidentified nauplii	25.5	0.2	7.3	—				
Unidentified copepedite/adult	13.6	4.3	38.0	0.3	75.2	95.0	68.9	1.7
Acartia spp.	6.7	2.7	11.0	0.8	0.1	<0.1		
Calanus spp.			0.4	0.1	2.7	0.5	0.4	<0.1
Centropages spp.			0.6	—				
Oithona spp.			0.5	—				
Pseudocalanus spp.	5.5	3.5	8.8	0.7	17.6	0.4	0.4	<0.1
Cirripedia								
Unidentified nauplii					0.1	<0.1		
Euphausiidae								
Unidentified calyptopis			0.4	<0.1				
Unidentified egg			29.0	0.3	1.6	0.3	9.5	<0.1
Unidentified nauplii			0.9	<0.1	0.1	<0.1	2.6	<0.1
Unidentified furcillia			0.2	0.1	0.4	<0.1		
Euphausia pacifica			1.1	74.7	<0.1	0.3	0.1	0.8
Thysanoessa spinifera					<0.1	0.2	14.8	75.2
Amphipoda								
Hyperiidea			0.1	0.3				
Mollusca								
Unidentified invertebrate egg			0.4	<0.1	1.3	<0.1	3.3	<0.1
Phytoplankton	—[a]	84.1	—	6.0	—	1.7	—	21.1
Unidentified Material			—	15.7	—	0.9	—	0.8
Number Analyzed	20		69		47		48	
Mean Fork Length in mm (SD)	215.2 (19.2)[b]		220.8 (3.1)		238.4 (3.1)		234.6 (2.9)	

[a] Prey item not counted or weighed.
[b] Measurements obtained from field samples (*n*=263) where stomachs were collected for diet analysis.


NEARSHORE
August 2000 & 2002
***n* = 53**

OFFSHORE
August 2000 & June/August 2002
***n* = 79**

Figure 16. The nearshore (<150 m isobath) and offshore (>150 m isobath) diets (wet weight composition) of Pacific sardine (*Sardinops sagax*) off Oregon from 2000 and 2002 GLOBEC Surveys.

TABLE 4
Fish predators of Pacific sardine (*Sardinops sagax*) off the Oregon and Washington coast

Predator	Scientific name	Size range (mm)	Length type	Length (FL, mm) of sardine eaten	Number of occurrences	Total number
Coho salmon juveniles	*Oncorhynchus kisutch*	252–259	FL	27–86	8	18
Coho salmon adults	*Oncorhynchus kisutch*	532–675	FL	190–205	2	3
Chinook salmon juveniles	*Oncorhynchus tshawytscha*	150–252	FL	20–56	22	38
Chinook salmon adults	*Oncorhynchus tshawytscha*	700–870	FL	125–250	4	4
Pacific hake	*Merluccius productus*	420–720	SL	190–215	9	12
Jack mackerel	*Trachurus symmetricus*	523–573	FL	99–145	9	13
Blue shark	*Prionace glauca*	1160	TL	210	1	1
Soupfin shark	*Galeorhinus galeus*	1360–1750	TL	200–240	2	13
Thresher shark	*Alopias vulpinus*	3200–3900	TL	*		3

*Regurgitated on deck after capture, not quantitative.

cold (Peterson and Schwing 2003) and sardine spawning success off the PNW appeared limited; few 0-age juvenile sardines appeared in the September Plume Surveys (fig. 11). Sardines that spawned from 1999 to 2002 were not abundant in the commercial fishery.

The commercial catch age-class and September size-class structure data suggest that sardines off the PNW consist of a local stock plus fish from California, but additional evidence is needed to identify that PNW sardines are a separate stock. There are many non-genetic techniques that could be used to identify stock differences, including parasites (Marcogliese et al. 2002), meristics (Smith 2005), otolith elemental composition (Milton and Chenery 2001), and morphometric methods (Felin 1954; Kinsey et al. 1994; Cadrin et al. 2005).

Habitat Analysis

Although the GAM analysis identified physical variables that appear to be related to the spatial distributions of sardines at various life-history stages, the amount of variability accounted for by these variables was fairly low. This may be due to the nature of the sampling such that, in some cruises, all habitats sampled may have been within the environmental tolerances of sardine. In addition, the highly contiguous distributions commonly observed with pelagic schooling fishes also present serious statistical problems of analysis. Finally, important mesoscale and fine-scale physical processes, such as fronts or eddies (e.g. Logerwell and Smith 2001; Nishimoto and Washburn 2002), may affect the distribution of all life stages. However, they are not likely to be resolved with our sampling strategy, thereby reducing our ability to identify physical and biological factors that affect sardine distributions. Many pelagic fishes change their behavior and distribution with time of day (Fréon et al. 1993; 1996; Fréon and Misund 1999). Sardines, for example, are known to make diel vertical migrations toward the surface at night (Giannoulaki et. al., 1999). Comparisons between day and night surface trawl catches off Oregon suggest that sardines have higher densities or are more catchable at the surface at night (Krutzikowsky and Emmett, 2005).

Some consistent patterns do emerge from the statistical analyses. Temperature and salinity seem to be important determinants of habitat for early life stages, and there may even be some threshold temperature level needed to induce spawning. Larger sardines appear to show an affinity for the lower salinity Columbia River plume water that may be more productive than oceanic waters. Catch rates of the more mobile juvenile and adult fishes are positively correlated with chlorophyll concentrations, which implies that these fish are migrating into or are maintaining their positions within productive areas necessary for faster growth or reproduction. Our analysis shows that the sardines' habitat requirements or preferences appear to change ontogenetically and that no one variable can explain their distribution throughout their life history.

Diet and Role in Ecosystem

Analysis of PNW sardine diets indicates that sardines consume primarily phytoplankton, copepods, and euphausiids. This is in general agreement with previous studies of sardine diets from British Columbia (Hart and Wailes 1931; McFarlane and Beamish 2001), Southeast Alaska (Wing et al. 2000), Western Pacific (Stovbun 1983; Kawasaki and Kumagai 1984), and the Benguela Current (Van Der Lingen 2002). The proportional importance of primary prey observed in the present study, however, varied spatially and temporally, and coincided with the spatial distribution of prey and the temporal variation in primary (chlorophyll *a*) and secondary production (neuston biovolume).

Sardine diets exhibited spatial heterogeneity in the prey indicative of the onshore/offshore plankton community composition and overall production. Nearshore sardines typically consumed more phytoplankton and copepods whereas offshore sardines consumed more euphausiids. This dietary pattern reflects the typical abundance of copepods and phytoplankton on the shelf

(Anderson 1965; Morgan et al. 2003) and euphausiids on the slope-offshore region (Swartzman 1999).

We did not find correlations between sardine diet (as a percent of body weight), neuston biovolume, proportion of phytoplankton in the diet, and 3 m chlorophyll *a* concentrations. In contrast, Hart and Wailes (1931) observed a moderate correlation (mean = 0.46) between sardine stomach biomass and zooplankton. The apparent lack of correlation between sardine diet and primary and secondary producers implies that sardines are feeding deeper in the mixed layer, possibly just above the thermocline at the chlorophyll maximum. At this depth, phytoplankton, copepods, and euphausiids may be more concentrated (Lamb and Peterson, 2005) and more efficiently obtained. Alternatively, feeding may have occurred at some distance from the capture location, or food resources were sufficiently patchy to yield low statistical correlation. Sardines did show strong seasonal and interannual variation in diet that covaried with changes in primary and secondary production.

The low contribution of copepods and the high amount of phytoplankton in the diet in August 2002 was likely due to the anomalous conditions experienced on the Oregon shelf at the time. During late summer 2002, entrainment of cool, nutrient-rich, subarctic water on the shelf resulted in very high primary productivity (Wheeler et al. 2003) but low copepod abundance (Goericke et al. 2004). The similarities between observed annual/seasonal ocean productivity and sardine diet reveal an important link between the physical oceanographic conditions and sardine trophic responses. Sardines may be an ideal indicator of oceanographic conditions because they filter feed through prey fields (Alamo and Bouchon 1987; James 1988), consuming organisms that are directly influenced by physical shifts in their environment.

Similar to the 1930s, sardines are presently prey for many large piscivorous fishes off the PNW, including adult Chinook and coho salmon (Chapman 1936). Our estimates of fishes that consume sardines are probably minimal because surface trawl nets were inefficient at capturing large, fast-swimming fishes. We suspect, for example, that albacore tuna (*Thunnus alalunga*) and large chub mackerel (*Scomber japonicus*) also eat sardines off Oregon and Washington.

The importance of sardines to PNW salmon life histories is difficult to determine at this time. As sardines have become abundant, salmonid runs in the Columbia River and elsewhere in the PNW have recovered significantly since 1999 (Williams et al. 2005). An increase in forage fish (including sardines) in the Columbia River estuary appears to have reduced Caspian tern (*Sterna caspia*) predation on juvenile salmon smolts.[4] Pacific harbor seals (*Phoca vitulina richardsi*), which also prey heavily on juvenile salmonids in coastal estuaries, are now consuming sardines off Oregon (Orr et al. 2004). Besides providing an alternative prey for juvenile salmonid predators (Pearcy 1992), abundant sardine populations may provide adult salmonids with additional calories, allowing them to grow larger, produce larger eggs, and improve hatching and alevin success (Fleming and Gross 1990). The effects of increased sardine abundance on other PNW fishery resources are unclear, but the high sardine biomass is likely to be important food for many different predators in this region.

Relationship to Ocean Conditions

It is believed that the abrupt decline in abundance of Pacific sardines in the late 1940s and 1950s, and the recent resurgence, is largely related to ocean temperature changes linked to climate or ocean regime changes (Jacobson and MacCall 1995; McFarlane et al. 2002; Chavez et al. 2003). During the warm regime of the 1930s–1940s, sardines in the California Current flourished, while during the cold regime of the 1950s–1970s, they declined. In the late 1970s, and perhaps again in the late 1980s, a new warm ocean regime began and sardines in the California Current responded favorably (McFarlane et al. 2002; Chavez et al. 2003). However, in 1999, the Northeast Pacific Ocean appeared to move into a new "cold" regime (Peterson and Schwing 2003), which was evidently not favorable for sardine spawning and recruitment. Our data indicate that this was particularly true for PNW sardines, as few small, 0-age sardines were captured from September 1999–2002 (fig. 11). However, this cool period did not last; both 2003 and 2004 were years with warm sea surface temperatures and apparent successful recruitment of 0-age sardines. If warm ocean conditions continue off the PNW, as expected given the long-term trend of warmer climate and oceans (Levitus et al. 2000), sardines will probably continue to spawn successfully off Oregon and Washington.

Northern anchovy (*Engraulis mordax*) and Pacific sardine populations have been observed to fluctuate out-of-phase with each other, probably because of different temperature preferences (Lluch-Belda et al. 1992; Chavez et al. 2003). However, this has not been observed in the Northwest; both northern anchovy and Pacific sardine populations (and other forage fish populations) have been increasing since 1999[5] and presently represent a substantial proportion of the pelagic nekton abundance off Oregon and Washington (Emmett and Brodeur 2000; Brodeur et al. 2004, 2005). As others (Jacobson and MacCall 1995) have found, our analysis revealed that sea surface temperature strongly influences sardine abun-

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[4] D. Roby, Oregon State University, Corvallis, OR, pers. comm.

[5] Emmett et al. unpub. ms

dance, distribution, and spawning success. Adult sardines, which migrate south to California during the winter, generally do not arrive to PNW coastal feeding grounds until sea surface temperatures exceed 12°C. This arrival usually occurs in July, after they have spawned in warmer (>14°C) waters offshore during June and July. Sardine spawning surveys and surface trawls off Oregon and Washington in July 2003 and 2004 found most adult sardines within 60 nm of shore.[6] Small juvenile sardines, in contrast, do not appear to migrate but over-winter in nearshore coastal waters, including the Columbia River estuary and Willapa Bay. One of us (Bentley) recently observed a die-off of juvenile sardines in the Columbia River estuary in December 2004, which was apparently related to high tides and high freshwater flows causing osmotic stress and death. A similar event was reported in the 1940s (Walford and Mosher 1941).

In conclusion, sardines have returned to the PNW in large numbers and have gone from being nonexistent to one of the dominant pelagic species in the northern California Current (e.g., Brodeur et al. 2004, 2005) in the span of slightly more than a decade. They presently support a healthy commercial fishery and are important prey for many large fishes. Sardines do not appear to have displaced other plankton-feeding pelagic schooling fishes, such as northern anchovy. Sardines may, in fact, play a role in the increase in salmon runs observed in the PNW since 1999. However, additional research needs to be done to confirm this. More importantly for management purposes, we need to determine whether the sardines spawning and residing off the PNW are a separate stock or just an extension of the California population.

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DISTRIBUTION AND BIOLOGY OF PACIFIC SARDINES (*SARDINOPS SAGAX*) OFF BRITISH COLUMBIA, CANADA

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ABSTRACT

Pacific sardines (*Sardinops sagax*) in the northeastern Pacific Ocean once supported one of the largest fisheries in the world, with catches off the west coast of Canada averaging 40,000 t annually from the mid-1920s to the mid-1940s. The stock collapsed in the late-1940s and disappeared from Canadian waters. In 1992, sardines were once again captured off the southwest coast of Vancouver Island. Abundance continued to increase off British Columbia, and by the mid-1990s experimental fisheries were initiated. Evidence of spawning was observed, and in some years sardines remained in Canadian waters year-round. The northern distribution of sardines continued to expand, and in the 1997–98 El Niño years sardines were found as far north as Alaska. In recent years, fish have been found infrequently in offshore areas but are abundant in the several large inlets on the west coast of Vancouver Island. In this paper we examine the distribution, biology, and ecology of sardines in British Columbia since 1992 and discuss sardine dynamics in relation to ocean temperature.

INTRODUCTION

The Pacific sardine (*Sardinops sagax*) constituted the largest fishery in British Columbia from the 1920s to the mid-1940s. Catches during this period averaged 40,000 t annually, then collapsed in 1947 as sardines disappeared from the British Columbia coast. The collapse of sardines off the west coast was historically cited as an example of overfishing (Hilborn and Walters 1992) rather than a result of distributional change, and sardines were not expected to return to Canadian waters (Murphy 1966; MacCall 1979). In Canada, the Pacific sardine was listed as a species of concern by the Committee on the Status of Endangered Wildlife in Canada (COSEWIC) in 1987 (Schweigert 1988).

Sardines reappeared in British Columbia waters in 1992 in commercial and research catches of Pacific hake (*Merluccius productus*) (Hargreaves et al. 1994), and an experimental scientific fishery was opened in 1995. Research surveys targeting sardines were first conducted in 1997, capturing the fish in large numbers in surface waters. The abundance of sardines in British Columbia waters increased through 1999, then began to decline in outer coastal waters as their numbers and range decreased. In the past two years, sardines have been a less abundant component of offshore waters but are still found in large numbers in the inlets of Vancouver Island's west coast. This recent reappearance of sardines off British Columbia has been linked to changes in climate/ocean conditions (McFarlane and Beamish 1999; McFarlane et al. 2000; McFarlane and Beamish 2001).

Sardine spawning in Canadian waters has historically been considered rare, and supporting evidence of it is circumstantial. Generally, these events were considered limited to unusually warm periods (DFO 2004). However, recent data suggest that sardines frequently remain in Canadian waters year-round. Evidence of successful spawning and juvenile populations indicates behavioral changes coincident with the recent re-expansion into Canadian waters (McFarlane and Beamish 2001).

This report presents recent distribution and biological data and fishery and management information on Pacific sardine. In addition, we examine regional distribution changes in relation to ocean conditions (sea surface temperature). These documented changes in sardine population abundance and dynamics in Canadian waters over the past decade will be useful in developing future coastwide (Mexico to Canada) assessments.

METHODS

Biological Data

Since the reappearance of sardines in 1992, over 40 surface-trawl surveys (see McFarlane and MacDougall 2001 for details of surveys) have been conducted to examine their abundance and biology (with the exception of 1994) using a model 250/350/14 midwater rope trawl (Cantrawl Pacific Ltd., Richmond, British Columbia). Catch and biological data have been collected for sardines during all research trawling operations since they reappeared in catches in 1992. Fork length (in mm), sex, and maturity were recorded for all sardines sampled. Based on visual assessment of gonads, sardine maturities were classified as immature, maturing, mature/ripe, or spent.

Plankton sampling was conducted during June in 1992 and 1993 and from May to September in 2004, using a 236 mesh Bongo VNH net, towed obliquely from the surface to depths ranging from 52 to 250 m, and retrieved at 1 m/s.

Sardine otoliths were collected from randomly selected samples of 50 fish during research cruises off the west coast of Vancouver Island (WCVI) from 1997 to 2002. Samples were collected from throughout the entire range of the fish. Otoliths were extracted from sardines during onboard sampling, or were extracted in the laboratory from sardines that were frozen, and processed at the Pacific Biological Station, Nanaimo, British Columbia. After otoliths were extracted, they were rinsed in water to cleanse and remove tissue and stored dry for subsequent aging. Otoliths were placed under a film of water in a shallow container and observed under a dissecting microscope on 25X power with a 10X eyepiece, using reflected light. Against a dark background, opaque bands appeared light, translucent bands appeared dark. Annuli were defined as the area consisting of one opaque zone (summer growth) and one translucent zone (winter growth). We have chosen a 1 January birthdate because that date does not straddle the growth cycle for a complete growth year. In our aging methodology, an otolith that displays one full light band and dark band is a 1-year-old. Similarly, for an older fish, an otolith showing four sets of light and dark bands is considered a 4-year-old.

Sardine stomachs were collected from randomly selected samples of 50 fish during trawl surveys conducted off WCVI from March–October 1997–2002, aboard the R/V *W.E. Ricker*. Stomachs were excised and preserved in 3.7% formalin. In the laboratory, contents were identified under a dissecting microscope to the lowest taxonomic group possible. Authors have omitted stomachs analyzed using methodology inconsistent with the described laboratory methods, along with stomachs collected in spring or fall, empty stomachs, and stomachs containing 100% scales or 100% digested material.

Prey item volume was expressed as a proportion of a full stomach and as an estimate of the item's volume in cubic centimeters. The degree of contents digestion was recorded as a percentage, with 0% denoting fresh contents. The contribution of each prey item was determined by its frequency of occurrence (%FO), average volume per stomach (%C), and proportion of overall volume of all stomach contents (%V). Prey items were assigned to a unique category for further analysis if present in at least 5% of the stomachs in a particular year (%FO ≥ 5%) and recorded in at least three of the five survey years. Prey items not meeting these criteria were combined in an "other" category.

Relative importance (RI) of each prey group was determined using a modification (King and Beamish 2000) of the index of relative importance (IRI) (Pinkas et al. 1971). Similar to the IRI, each prey item's RI describes its average volume per stomach, how many fish eat that prey item, and how much that prey item contributes to the total volume of food consumed by all sardines. The RI ranges from 0, where a prey item is not consumed at all, to 20,000, where a prey item is consumed exclusively. In this report, the RI values are expressed as a percent of the maximum attainable value of 20,000 (%RI) to allow for a direct comparison between prey items. Percent RI values are not cumulative within a year; the %RI values for all prey items within a year may sum to more than 100.

RI = %FO x (%C + %V) where:

%FO = % frequency of occurrence: % of stomachs in which prey groups are present

%C = the average % volume of stomach contents contributed by the prey group

%V = the ratio of the total prey group's volume to the total volume of the stomach contents.

Three-way-graphs were used to show which variable in the index (i.e. %V, %FO, or %C) was the most influential in determining the %RI value.

Abundance Data

Biomass estimates were calculated from data collected during directed abundance cruises conducted in July of 1997, 1999, and 2001. Biomass estimates were calculated according to the method described in Beamish et al. (2000). The WCVI was partitioned into six major regions determined during a cruise in 1997. The total volume for each region was calculated by multiplying the estimated area of each region by the maximum net depth (30 m, or 0.03 km).

The volume swept during each set was determined by multiplying the area of the midwater trawl net used during fishing operations by the distance traveled during fishing. Abundance in numbers of sardines was converted to weight (kg) by multiplying abundance in numbers by average weight (kg) of an individual sardine (calculated to be 0.165 kg) from 1997, 1999, and 2001, as the average size of fish during these years was similar. Areas where sardines were captured in three or fewer sets were not included in abundance estimates. Total abundance for each region was determined from numbers of sardines in the swept volume, extrapolated to the total volume. Minimum and maximum estimates were

TABLE 1
Catch (t) of Pacific sardine (*Sardinops sagax*) by Statistical Area in the experimental fishery since 1995 based on validated landings[3]

	Area										
	Queen Charlotte Sound Inlets			North West Vancouver Island Inlets			South West Vancouver Island Inlets		Offshore South West Vancouver Island		
Year	8	10	12	25	26	27	23	24	121	123	Total (t)
1995				23							23
1996					80						80
1997			27				4				31
1998		162	301	94	9			109			675
1999	8	352	346	9	245	100	74				1134
2000	55		80	768	145	302	208				1558
2001	85		41	436	68	395	183		41	19	1268
2002		370	54	297	41	147	104				1013
2003				82		36	921	39			1078
2004		81		2266	829	69	192	822			4259

*Note: Current as of 11 January 2005. Last landing date included is 8 December 2004.

TABLE 2
Canadian commercial sardine catch (t) by month from 2000 to 2004

Year	Jul	Aug	Sept	Oct	Nov	Dec	Jan	Feb	Total
2000/01		496	583	183	457				1559
2001/02		328	785	283					1266
2002/03			448	161	96	111			1013
2003/04	86	37	713	241			135	63	1077
2004/05		52	1586	1762	859				4258

determined using the 95% confidence interval for the calculated average swept volume within each major area.

Temperature Data

Sea surface temperature data (SST) were assessed from three coastal buoys (buoy 46206, La Perouse; buoy 46132, South Brooks; buoy 46185, South Hecate Strait), three offshore buoys (buoy 46207, East Dellwood; buoy 46205, West Dixon Entrance; buoy 46004, Middle Nomad), and three lighthouse stations (Amphitrite Point, Kains Island, and McInnes Island). Lighthouse data were compiled from a British Columbia lighthouse database[1] and anchored ocean buoy temperature data were provided by Roy Hourston and Richard Thomson[2]. Monthly mean temperatures from June to August for 1990 to 2003 were calculated from daily mean data when available.

RESULTS

Fishery and Research Catches

In 1992, sardines were captured in research and commercial sets targeting Pacific hake (*Engraulis mordax*). By 1995 sardines were noted in abundance in Nootka Sound, WCVI, and a small experimental fishery was initiated (tab. 1). Expansion of the experimental fishery proceeded slowly, and in 1997 this fishery was extended for a three-year period with a pilot individual quota system consisting of seven participants with 73 t of allocations (of a total quota of 508 t, 31 t were landed; tab. 1). In 1999, the quota was increased to 1089 t (145 t/vessel plus 73 t for research). In 2000, the quota was increased to 180 t per vessel; and in 2004 it was increased again to 300 t per vessel. Landings increased from 676 t in 1998 to 1559 t in 2000 and averaged about 1000 t through 2004 when they increased again to 4258 t (tab. 1). The delisting of sardine as a species of concern by COSEWIC in 2002 provided additional opportunity for expanding the commercial fishery, but market conditions were unfavorable. In both 2001 and 2002 experimental fisheries occurred with gillnet and traps, but they were subsequently discontinued. Since the inception of the sardine fishery, the majority of the catch has been taken on the WCVI primarily from areas 25 and 26 (tab. 1). In some

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[1] BC lighthouse database is available at URL: <http://www-sci.pac.dfo-mpo.gc.ca/osap/data/searchtools/searchlighthouse_e.htm> [Accessed on: 30 August 2005].

[2] Roy Hourston Institute of Ocean Sciences, 9860 West Saanich Road, P.O. Box 6000 Sidney, British Columbia, Canada,V8L 4B2; Richard Thomson, Institute of Ocean Sciences, 9860 West Saanich Road, P.O. Box 6000 Sidney, British Columbia, Canada,V8L 4B2.

[3] For detailed description of Statistical Areas see website URL <http://www.pac.dfo-mpo.gc.ca/ops/fm/Areas/areamap_e.htm>. [Accessed on: 30 August 2005].

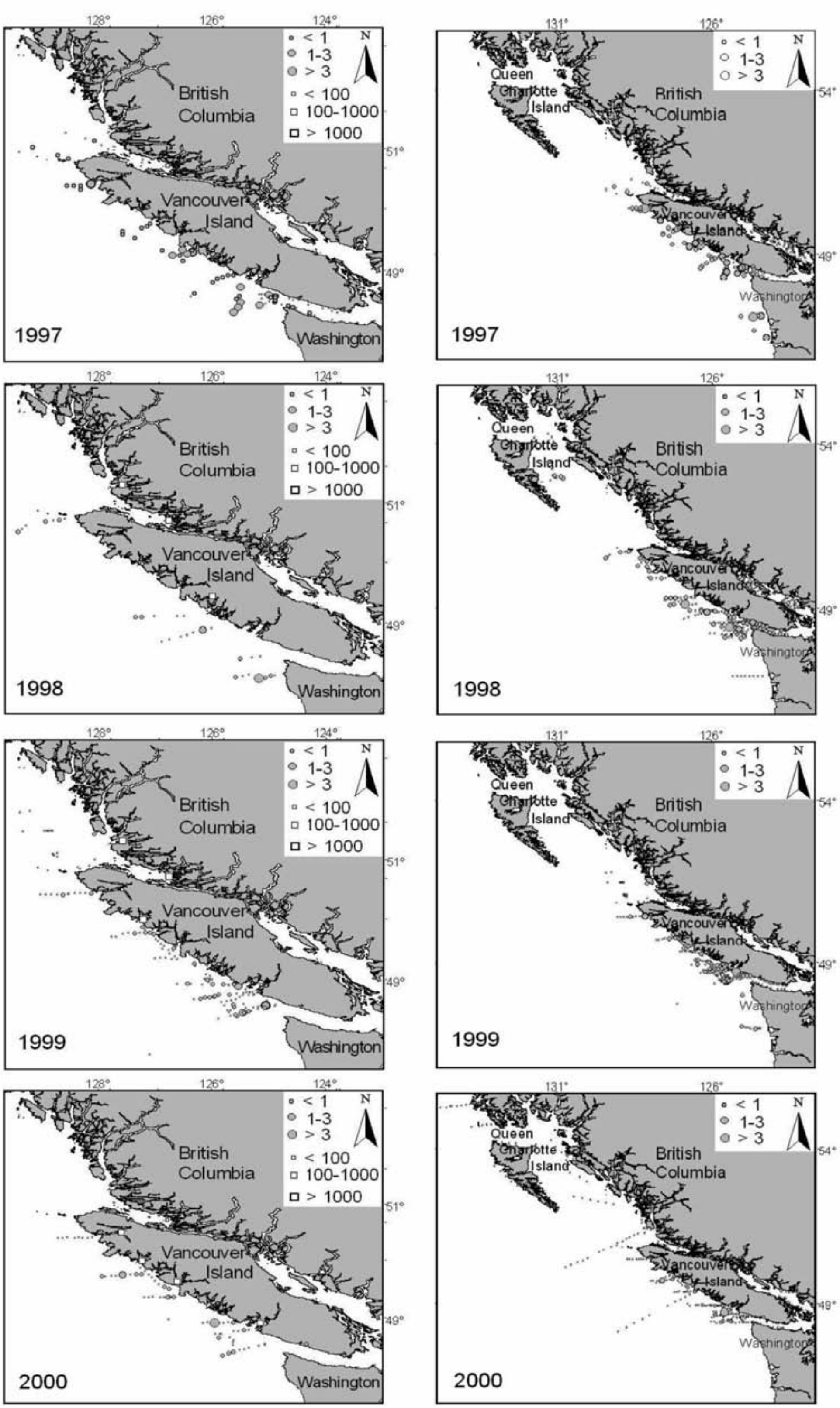

Figure 1. Pacific sardine (*Sardinops sagax*) distribution in research and commercial surveys, for all months and June through August 1997–2004. Panels on the right illustrate research catch from all months of the year; left hand panels illustrate research catch from June to August only and commercial catches. Note: circles represent sites of research catch, squares represent sites of commercial catch. Catches in tons.

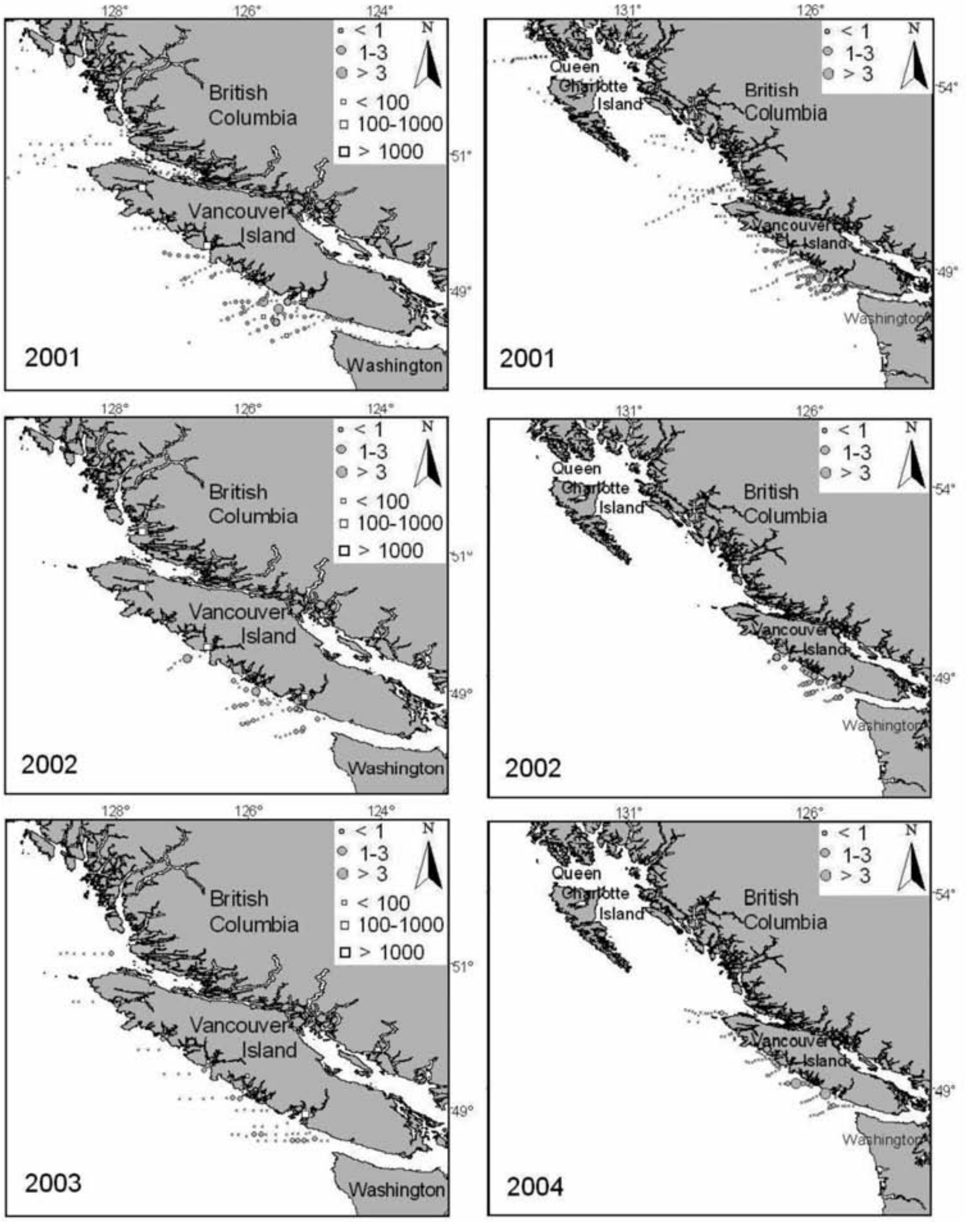

Figure 1 (continued). Pacific sardine (*Sardinops sagax*) distribution in research and commercial surveys, for all months and June through August 1997–2004. Panels on the right illustrate research catch from all months of the year; left hand panels illustrate research catch from June to August only and commercial catches. Note: circles represent sites of research catch, squares represent sites of commercial catch. Catches in tons.

years, the bulk of the catch came from inlets off Queen Charlotte Sound (tab. 1) and from as far north as Smith Inlet. The bulk of the annual catch has been taken in September and October (tab. 2).

Distribution

From 1992 to 1996 small numbers of sardines were captured in both commercial and research sets targeting Pacific hake off the southwest coast of Vancouver Island. Since 1997, large numbers of sardines have been captured in surface water research sets targeted on sardine off the west and northeast coasts of Vancouver Island, Queen Charlotte Sound, and in a small commercial fishery for sardines in inlets surrounding Vancouver Island. From 1997 to 2000, sardines were captured in cruises during February to April and June to November, with the majority of sardines captured between June and August. From 1997 to 1999, sardines were found in the Strait of Juan de Fuca and as far north as the east coast of Queen Charlotte Sound. In 1998, sardines were also found on the northeast coast of Vancouver Island, the southern Strait of Georgia, Hecate Strait, and in waters

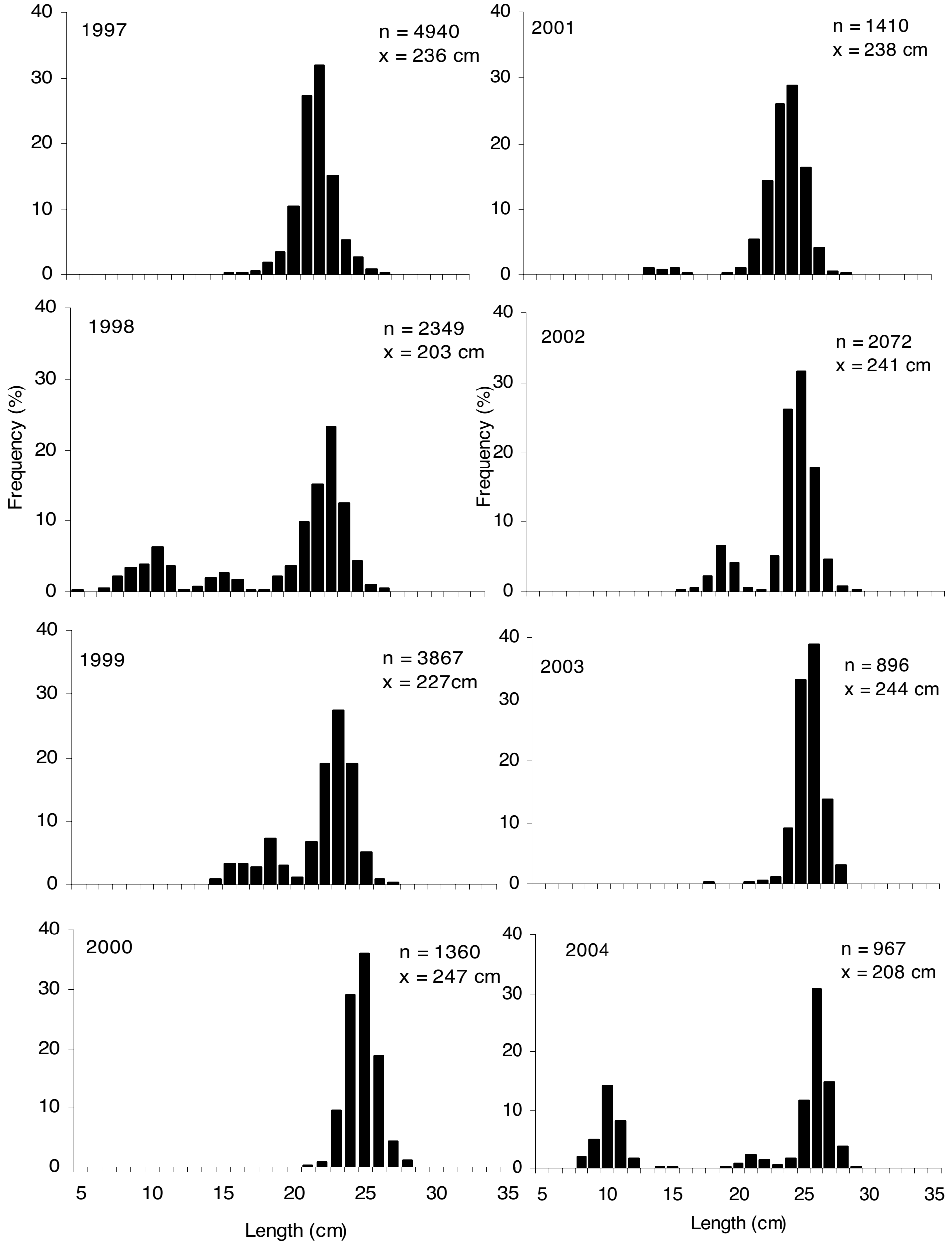

Figure 2. Length frequency data of Pacific sardines (*Sardinops sagax*) captured during research cruises off WCVI, 1997–2004.

off southeast Alaska (McFarlane and Beamish 2001). The sardine distribution in 2000 was concentrated on the WCVI and ranged as far south as Barkley Sound and as far north as mainland British Columbia, north of Vancouver Island. From 2001 to 2003, sardine distribution became progressively concentrated near shore along the southwest Vancouver Island coast and progressively less prevalent in research cruises. By 2004, sardines were rarely captured offshore or along the research grid; however, large catches of sardines were made in inlets and the shallows along the WCVI, and in 2004 in Queen Charlotte Sound inlets (fig. 1).

Abundance

Biomass estimates were calculated from directed abundance cruises conducted in July of 1997, 1999, and 2001: 88,843 t (95% CI = 66,947 – 136,288 t), 79,393 t (95% CI = 64,656 – 100,972 t), and 43,845 t (95% CI = 33,839 – 62,336 t), respectively. McFarlane and Beamish (2001) present detailed abundance estimates for 1997 and 1999. The 2001 estimate is based on the same methodology. We also note that the 2001 estimate of 43,845 t is from the southern portion of the WCVI only. These are minimum estimates as they included neither the sardines in the large inlets along the WCVI, nor the

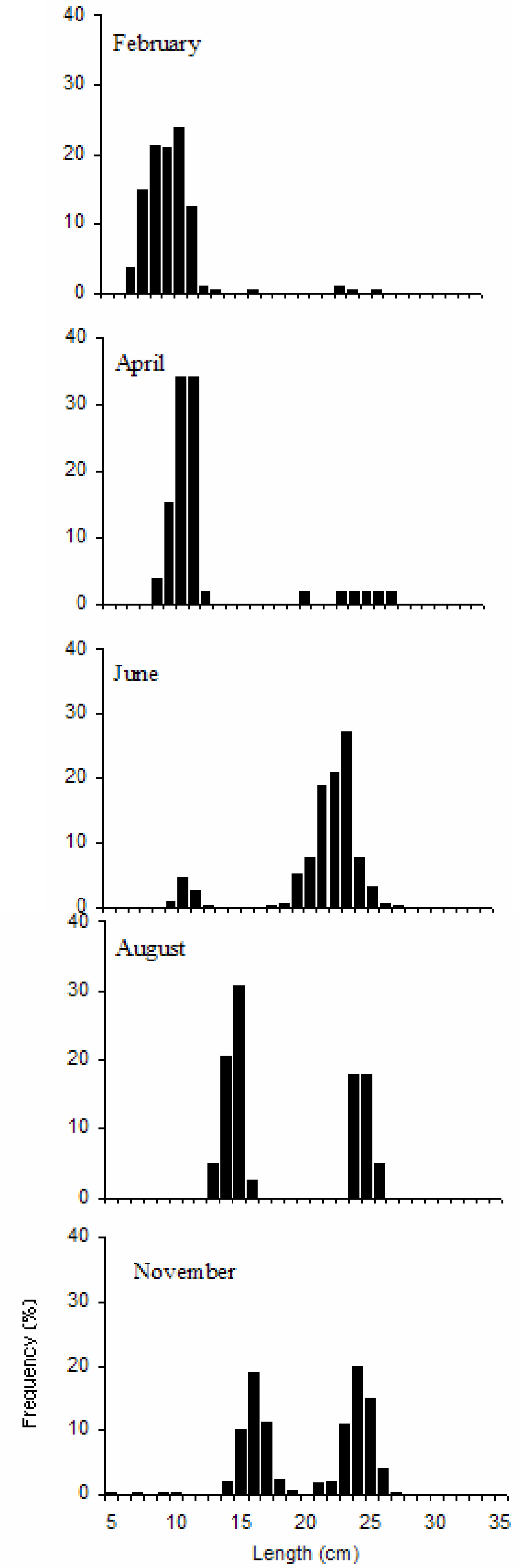

Figure 3. Pacific sardine (*Sardinops sagax*) length frequency for February to November 1998 collected throughout the year off WCVI. Note the appearance and persistence of young-of-the-year (1997 year-class).

large concentrations north of the survey area on the northeast tip of Vancouver Island. They are also based on the unlikely assumption that sardine catchability was 100%.

Biology

Length and Age A total of 17,888 sardine lengths have been recorded from research surveys since 1992 (fig. 2). The majority of lengths have been collected from summer and fall cruises. Lengths ranged from 50 mm in 1998 to 349 mm in 1997; however, only in 1998 and 2004 were sardines smaller than 140 mm sampled. Mean lengths ranged from 203 mm in 1998 to 247 mm in 2000. During 1998 and 2004, surveys conducted on the WCVI throughout the year captured sardines. For example, in 1998 a mode of small fish (50 mm to 120 mm) is present in the length frequency data representing the 1997 year class. These fish can be tracked through the year as a mode of 110 mm in February, April, and June; 150 mm in August, and 160 mm in November (fig. 3).

A similar length distribution progression was present throughout the year in 2003/2004. The results suggest juvenile sardines survive and remain in Canadian waters year-round. There was no difference in the mean lengths of sardines captured in northern (samples from Nootka Sound and north: 49.50°N; 126.56°W) or southern (samples collected south of Nootka Sound) waters during the study period (fig. 4).

Ages have been estimated for a total of 1859 sardines since 1999. Ages range from 1 to 9 years (fig. 5). From 1999 to 2002, the average was between 4.6 and 5.4 years, with a modal age of 5 years. In 2003 and 2004 more older fish were present in Canadian waters (fig. 5); the average age in 2004 was 6.5, with a modal age of 7, and 83% of sampled fish were 6 or older. Analysis of age by area since 1999 (tab. 3) indicates a trend for older fish to be present in areas in or north of Nootka Sound (49.50°N; 126.56°W) (North).

Maturity A total of 2893 sardines were sampled from research surveys from 1992 to 2004. Mature sardines and sardines in spawning condition were dominant in all years (fig. 6).

Egg surveys Sardine eggs were collected from oblique plankton tows in 1992, 1993, and 2004 (fig. 7). In 1992, five of eight plankton tow samples contained sardine eggs; in 1993 only one of eight samples contained sardine eggs, while in 2004 ten samples contained eggs. In 2004, sardine eggs were recovered from samples collected from 27 May to 7 September, at depths ranging from 0 m to 256 m (tab. 4).

Stomach Contents Analysis A total of 1231 stomachs were examined from research cruises off the WCVI from 1997 to 2002. Of these, 362 stomachs were collected during summer months (June to August), examined using

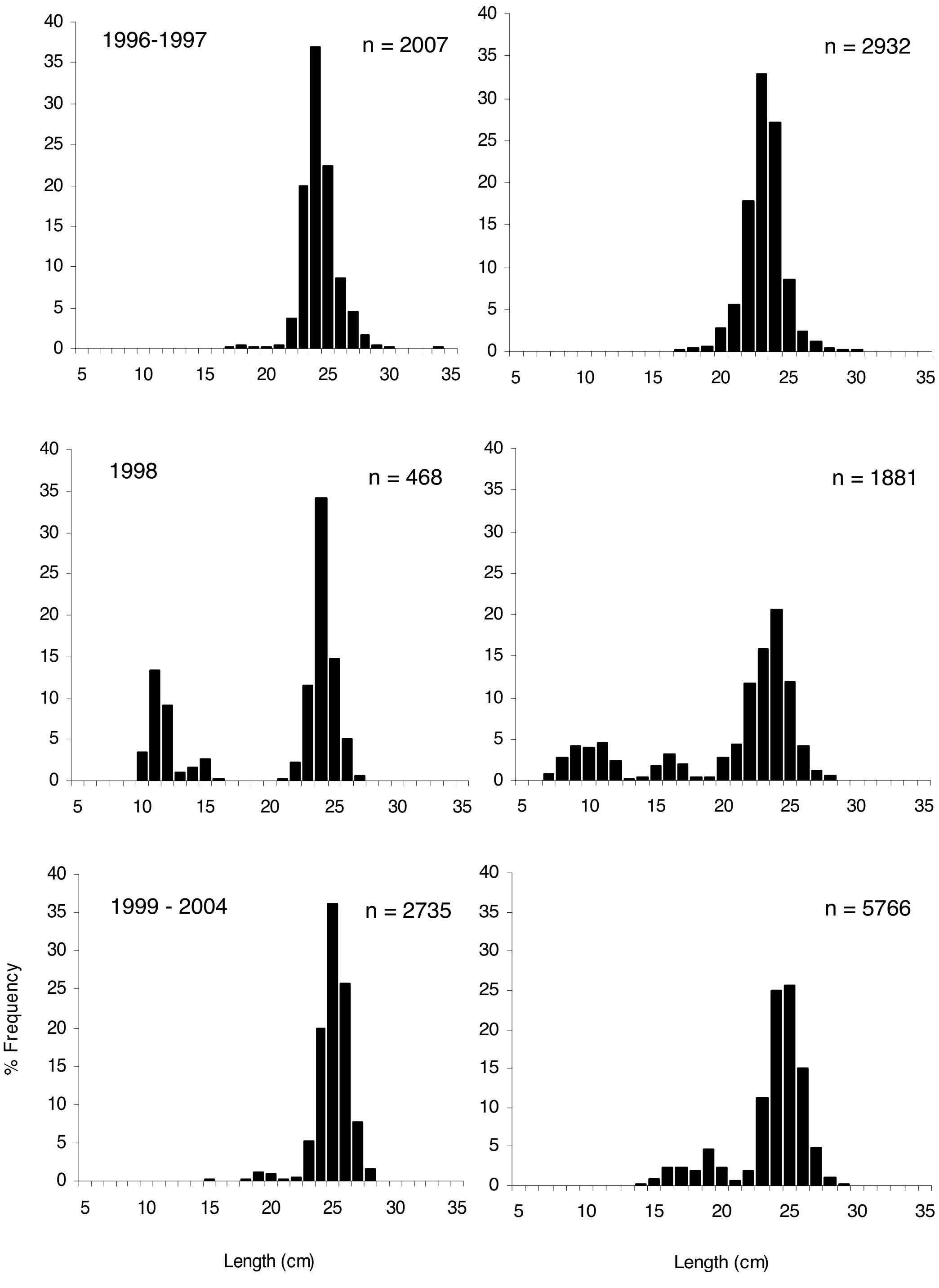

Figure 4. Length-frequency of Pacific sardine (*Sardinops sagax*) captured in or north of Nootka Sound (49.50° N; 126.56° W) (North: Left panels) compared with sardine captured south of Nootka Sound (South: Right panels), 1996–2004.

standardized laboratory procedures, and contained prey items (i.e. volume was not 100% digested material or scales). Consequently, they were included in this report (tab. 5). Mean volume per stomach (for stomachs collected from June to August) declined yearly from 0.86 cc in 1997 to 0.13 cc in 2001, while the largest volume of prey items was recorded in 2002 (average 1.7 cc per stomach). The mean percent of digested material per stomach ranged from a low of 29% in 1998 to a high of 90% in 2001. Despite the paucity of identifiable contents from 2001 samples, these data have been included to maintain the time series.

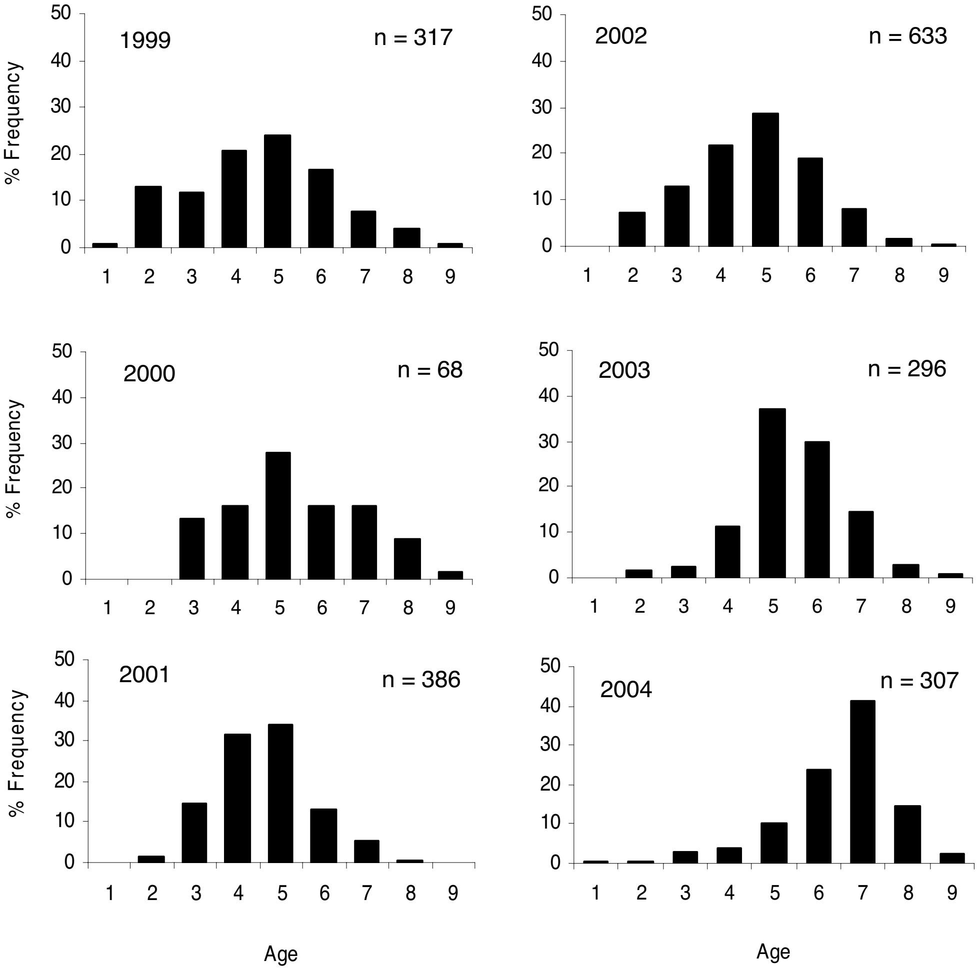

Figure 5. Age-frequency from Pacific sardines (*Sardinops sagax*) captured during research and commercial cruises off WCVI, 1999–2004.

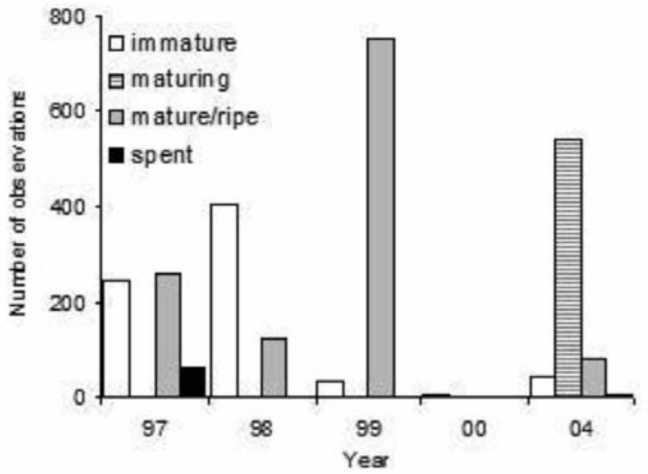

Figure 6. Maturity stages for Pacific sardines (*Sardinops sagax*) captured in research cruises off WCVI, July–August 1997–2000 and 2004.

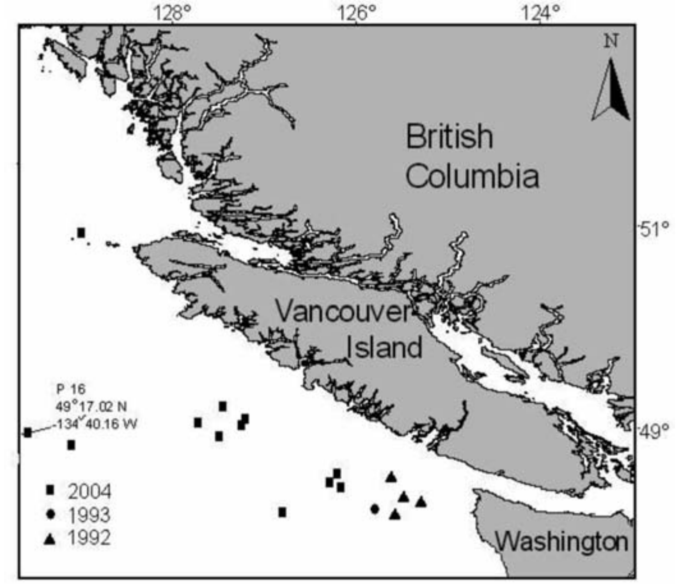

Figure 7. Locations of plankton tows (bongos) in which Pacific sardine (*Sardinops sagax*) eggs were present, 1992, 1993, and 2004.

TABLE 3

Mean age and range of Pacific sardine (*Sardinops sagax*) captured off WCVI, 1999–2002, 2003 and 2004. North includes sardines captured in or north of Nootka Sound (49.50°N; 126.56°W) (North) compared with sardines captured south of Nootka Sound

	1999–2002		2003		2004	
	n	mean (range)	*n*	mean (range)	*n*	mean (range)
North	1014	4.9 (2–9)	148	5.46 (2–9)	109	6.84 (4–9)
South	242	4.1 (2–9)	49	5.25 (3–7)	198	5.0 (1–9)

TABLE 4

Location (latitude and longitude) of oblique plankton tows in which Pacific sardine (*Sardinops sagax*) eggs were present: 1992, 1993, and 2004

Station	Date	Latitude	Longitude	Depth(m)
COPRA	1992 (June–Aug)	within 48°40 and 49°00	within 125°30 and 126°00	n/a
COPRA	1993 (June–Aug)	within 48°40 and 49°00	within 125°30 and 126°00	n/a
A4	2004/5/27	48° 15.01	126° 40.02	0–250
LC09	2004/5/27	48° 26.00	126° 13.79	0–249
A1	2004/5/27	48° 29.93	126° 6.36	0–178
CS05	2004/5/29	50° 56.01	128° 59.99	0–52
LG09	2004/5/31	48° 51.16	127° 19.45	0–250
LG07	2004/5/31	48° 59.42	127° 0.70	0–248
P08	2004/6/3	48° 49.03	128° 40.04	0–249
P16	2004/8/23	49° 17.02	134° 40.16	0–256
LG09	2004/9/7	48° 51.18	127° 19.40	0–250
LG07	2004/9/7	48° 58.76	127° 7.42	0–250

TABLE 5

Summary of stomach analysis for Pacific sardines (*Sardinops sagax*) captured off WCVI, 1997–2002. Stomachs from this list were included in the following report if they were analyzed using described methodology, collected in summer (June–August) months, and contained identifiable prey (i.e. did not contain 100% digested matter nor 100% scales)

Year/Month	# of stomachs analyzed	# by standard lab method	# empty	# 100% digested or 00% scales	# stomachs summarized for report	Total volume	Volume without digested	Average volume per stomach
1997								
June	549	67	0	51	16	44.50	6.24	0.67
July	22	5	0	5	0	4.80	0.54	0.96
August	53	53	0	39	14	50.80	15.26	0.95
October	15	15	0	14	1	14	7.20	0.92
1997 Total	**639**	**140**	**0**	**109**	**31**	**114.1**	**29.24**	**0.81**
1998								
May	14	14	3	3	8	6.90	6.40	0.69
June	57	57	0	3	54	30.76	19.96	0.54
August	14	14	1	0	13	11.40	11.35	0.87
September	45	45	13	2	30	7.38	0.44	0.21
October	20	20	1	10	9	4.90	1.24	0.26
1998 Total	**150**	**150**	**18**	**18**	**114**	**61.34**	**39.39**	**0.46**
1999								
March	30	30	0	0	30	13.50	4.61	0.45
July	81	81	1	0	80	16.50	11.82	0.21
August	45	45	0	0	45	5.80	2.20	0.13
1999 Total	**156**	**156**	**1**	**0**	**155**	**35.8**	**18.63**	**0.23**
2000								
September	74	74	0	0	74	9.50	0.53	0.13
2000 Total	**74**	**74**	**0**	**0**	**74**	**9.50**	**0.53**	**0.13**
2001								
July	38	38	0	0	38	4.80	0.30	0.13
August	22	22	0	0	22	3.70	0.25	0.17
October	50	50	0	2	48	5.70	0.70	0.11
2001 Total	**110**	**110**	**0**	**2**	**108**	**14.20**	**1.25**	**0.13**
2002								
August	80	80	0	0	80	136.1	90.1	1.701
September	22	22	0	0	—	21.2	6.02	0.9636
2002 Total	**102**	**102**	**0**	**0**	**80**	**157.3**	**23.735**	**1.33**

TABLE 6
Pacific sardine (*Sardinops sagax*) diet composition by year, 1997–2002. Data from summer months (June–August) only

	Euphausiid	Copepod	Diatoms	Euphausiid eggs	Oikopleura	Eggs	Crab zoea	Cladoceran	Barnacle nauplii	Fish eggs	Cyclopoid	Amphipod	Other*
1997 summer: 30 stomachs													
%C		21.05	0.50	0.00	0.00	0.00	5.00	3.67	0.00	0.00	0.00	0.00	0.33
1.00													
% FO	56.67	6.67	0.00	0.00	0.00	20.00	26.67	0.00	0.00	0.00	0.00	3.33	3.4
% V	59.02	1.64	0.00	0.00	0.00	17.16	9.20	0.00	0.00	0.00	0.00	0.47	3.3
%RI	22.69	0.07	0.00	0.00	0.00	2.25	1.72	0.00	0.00	0.00	0.00	0.01	0.1
1998 summer: 67 stomachs													
%C	18.21	1.05	36.40	21.01	0.00	0.00	0.00	0.00	0.31	0.01	0.07	1.05	2.5
% FO	23.88	17.91	74.63	74.63	0.00	0.00	0.00	0.00	7.46	1.49	1.49	11.94	11.5
% V	35.18	3.09	33.11	19.83	0.00	0.00	0.00	0.00	0.32	0.02	0.08	1.68	4.5
%RI	6.38	0.37	25.94	15.24	0.00	0.00	0.00	0.00	0.02	0.00	0.00	0.16	0.25
1999 summer: 125 stomachs													
%C	0.09	17.23	2.40	13.34	16.65	0.93	0.34	0.17	0.14	0.52	0.18	0.22	0.1
% FO	1.59	95.24	46.03	65.08	37.30	9.52	10.32	2.38	11.90	7.94	10.32	3.17	1.3
% V	0.36	31.17	5.55	20.31	36.48	2.13	1.17	0.21	0.22	1.64	0.23	0.50	0.1
%RI	0.00	23.05	1.83	10.95	9.91	0.15	0.08	0.00	0.02	0.09	0.02	0.01	0.05
2001 summer: 60 stomachs													
%C	0.50	2.052	2.00	0.17	0.15	0.081	0.823	0.1	0.066	0.00	0.162	0.13	0.01
% FO	8.33	95.00	71.67	15.00	8.33	1.67	3.33	10.00	6.67	0.00	10.00	6.67	1.6
% V	8.70	35.45	32.44	2.84	1.84	2.51	8.53	1.51	1.17	0.00	2.01	2.68	0.3
%RI	0.38	17.81	12.34	0.23	0.08	0.02	0.16	0.08	0.04	0.00	0.11	0.09	0.01
2002 summer: 80 stomachs													
%C	9.61	19.58	25.06	1.11	5.21	0.00	0.14	2.01	1.10	0.28	0.08	0.00	0.2
% FO	78.75	98.75	100.0	37.50	73.75	0.00	8.75	58.75	53.75	3.75	7.50	0.00	9.1
% V	1.07	47.18	35.31	0.00	7.26	0.00	0.18	5.01	3.84	0.06	0.00	0.00	0.1
%RI	4.21	32.96	30.19	0.21	4.60	0.00	0.01	2.06	1.33	0.01	0.00	0.00	0.1

* "Other" category includes barnacle cyprids, crab megalops, algae, shrimp zoea, fish larvae, gastropod, ostracod, and chaetognath. Individuals from these groups occurred in fewer than 5% of stomachs per year and in two or less years of data.

In 1997, the total volume of identifiable stomach contents (*n* = 30) was 22.04 cc (tab. 5) from which seven prey items were identified (tab. 6). Euphausiids were the most important (%RI of 23%), with importance influenced mainly by %FO and %V (fig. 8a). Specifically, euphausiids were identified from over 55% of sardine stomachs (%FO) and contributed nearly 60% of the overall stomach contents volume (%V), resulting in the highest %RI value calculated from 1997 data. From 1998 samples, 67 stomachs had a total identifiable volume of 31.31 cc (tab. 5). Thirteen prey items were identified (tab. 6), with three dominant items: phytoplankton (diatoms) (%RI = 26), euphausiid eggs (%RI = 15), and euphausiids (%RI = 6) (fig. 8b). In 1999 samples, 18.63 cc of contents were examined from 125 stomachs. Fourteen prey items were identified with copepods (%RI = 23%, found in 96% of stomachs), euphausiid eggs (%RI = 11%), and oikopleurids (%RI = 10%) identified as important prey items (fig. 8C). No stomachs were collected in the summer months in 2000. In 2001, 60 stomachs were collected. Total volume of identifiable contents was only 0.55 cc, as digested material accounted for over 90% of the volume in each stomach (tab. 5). Twelve prey items were identified at very low volumes. Copepods (%RI = 18%) were the most important, found in 95% of the stomachs, and diatoms (%RI = 12%) were also important (tab. 6; fig. 8d). In 2002, a total volume of identifiable contents of 90.10 cc was collected from 80 stomachs. Thirteen prey items were identified, characterized by a high frequency of occurrence and small volume contributions similar to 2001. Copepods and diatoms dominated the sardine diet (%RI of 33% and 30% respectively), were found in nearly every stomach, and were substantially more important than other prey items (fig. 8e).

In general, the majority of identifiable stomach contents consisted of five prey items: phytoplankton (diatoms), euphausiids, euphausiid eggs, copepods, and oikopleurids (larvaceans). The relative contribution by each of the prey items varied considerably (fig. 9). The categories of prey items found most often in our study are consistent with major food items found by Hand and Berner (1959), Radovitch (1952), and Ahlstrom (1960). For example, euphausiids were the most important prey item in 1997 but were virtually absent in 1999 and 2001. In contrast, phytoplankton (mainly diatoms) were absent in 1997 but were the most important prey item in 1998 (figs. 9 and 10). Copepods were important in 1999

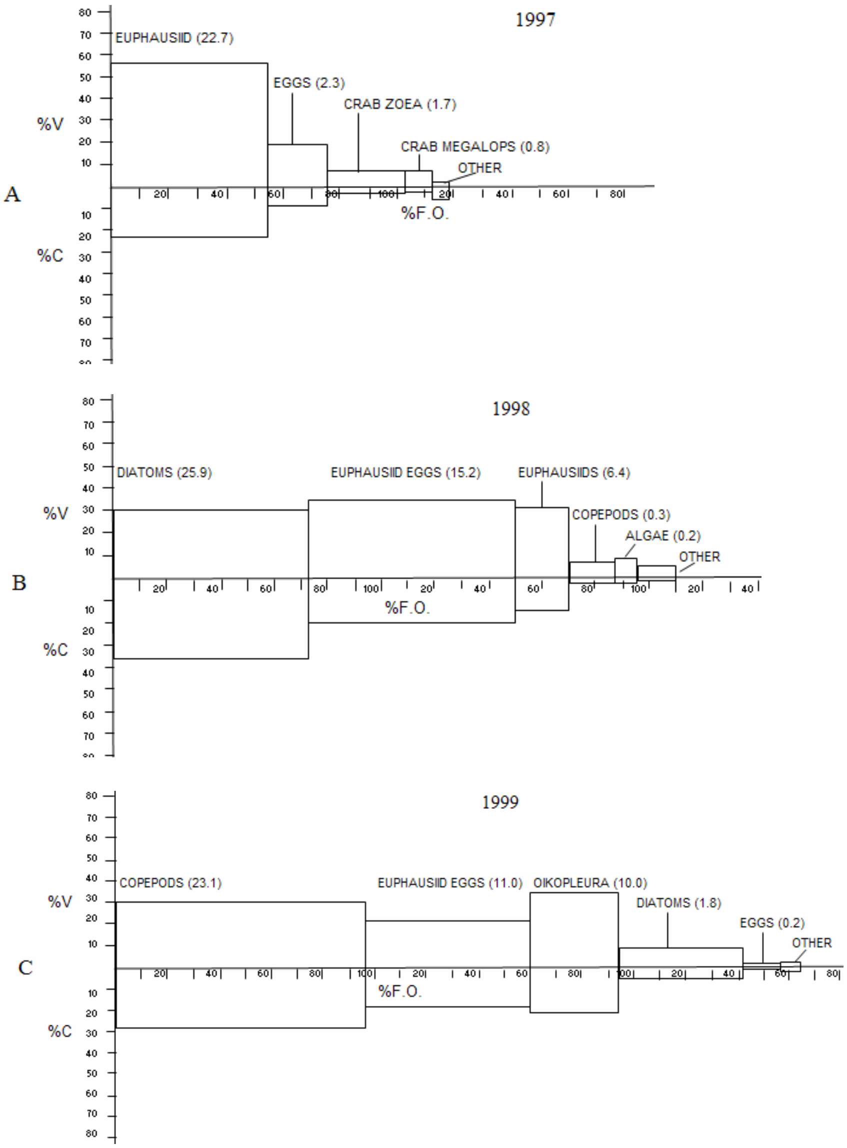

Figure 8. Three-way boxplots illustrating Relative Importance (%RI) values for prey items from Pacific sardine (*Sardinops sagax*) stomachs collected in (A) 1997, (B) 1998, and (C) 1999. Other category contains items with %RI values less than 0.1 for that year and may include: amphipod, barnacle nauplii and cyprids, chaetognath, cladoceran, copepod, crab megalops and zoea, cyclopoid, euphausiid, fish eggs and larvae, gastropod, oikopleura, and shrimp zoea.

and 2001 but were rarely consumed in 1997 and 1998. The absence of copepods in the sardine diet in 1997 may be coincident with a marked decrease in total copepod abundance in the North Pacific (Ocean Station Papa) in the spring of 1997 (Goldblatt et al. 1999) and illustrates the opportunistic feeding behavior of sardines.

Temperature The apparent change in the distribution of sardines in Canadian waters from offshore waters to inshore waters since 2002 was investigated by analyzing recent SST data from lighthouses and ocean buoys (fig. 11). We examined recent trends in SST for June, July, and August; the likely period of arrival of sardines in British Columbia waters. It is evident from the lighthouse data that in most years, with the exception of the 1992–93 and 1997–98 El Niño years, that surface waters did not reach 12°C until July (fig. 12). Similarly, the inshore buoys 46132 off Brooks Peninsula and 46185 in Hecate Strait did not reach 12°C until July. Only buoy 46206 on La Perouse bank consistently experienced SSTs above 12°C in all years in June (fig. 12). The offshore buoys consistently indicated colder conditions than the inshore buoys with SSTs in some years not reaching 12°C until August (i.e. 1999; fig. 13). In fact, buoy 46207 off the north end of Vancouver Island also indicated a declining trend in SST during June. The SST data from this region suggest that conditions in the offshore areas

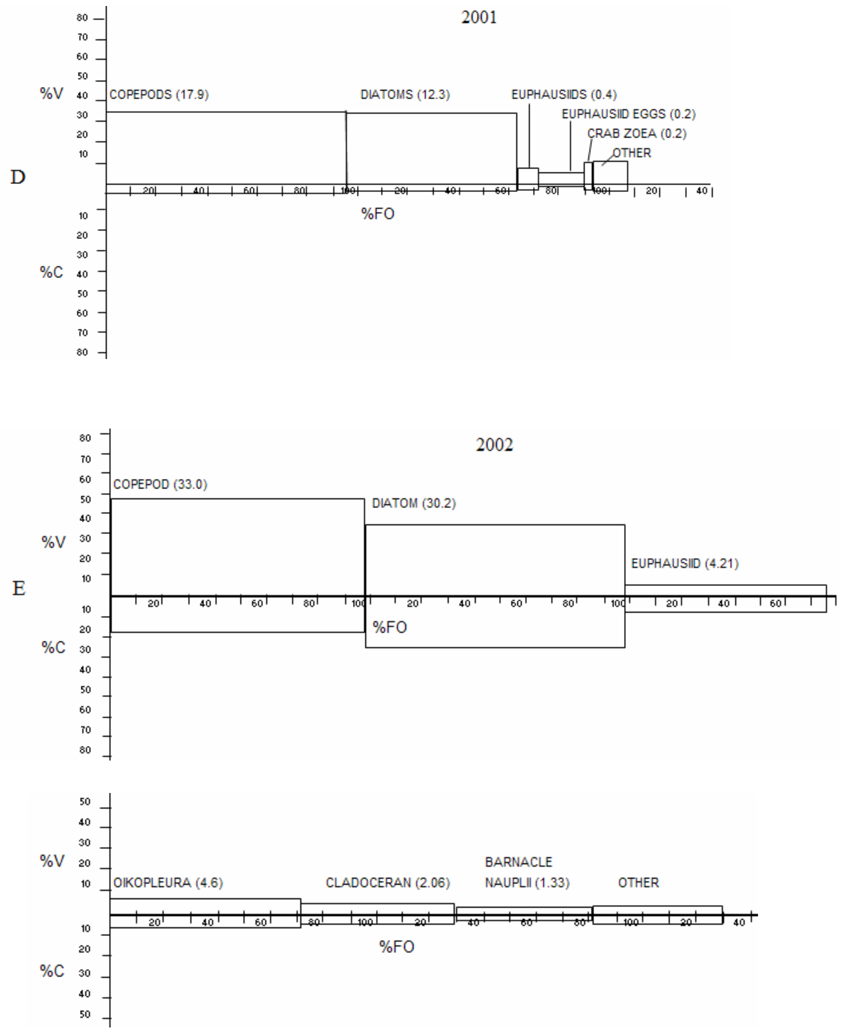

Figure 8 (continued). Three-way boxplots illustrating Relative Importance (%RI) values for prey items from Pacific sardine (*Sardinops sagax*) stomachs collected in (D) 2001, and (E) 2002. Other category contains items with %RI values less than 0.1 for that year and may include: amphipod, barnacle nauplii and cyprids, chaetognath, cladoceran, copepod, crab megalops and zoea, cyclopoid, euphausiid, fish eggs and larvae, gastropod, oikopleura, and shrimp zoea.

have been less favorable to sardines than in the inshore waters and that in recent years the highest water temperatures have occurred in the inshore areas near the mouth of Barkley Sound early in the year.

DISCUSSION

The management of the sardine fishery in Canada is based on the presumption that a portion of the population will continue to migrate north and be accessible to local fishers. The estimate of the migration rate of sardines into Canadian waters is based on the historically observed catch of sardines in Canada relative to that in the United States. From 1916 to 1947, the Canadian catch amounted to about 10% of the combined catch, suggesting on average a 10% annual northward migration rate. From the mid-1990s to 2001, sardines were widely distributed in the offshore areas near Vancouver Island, and their relative abundance could be determined by a standardized trawl survey. These surveys supported the 10% annual migration rate. However, more recently it appears that the bulk of the sardine migration has contracted shoreward and into the inlets along the WCVI where they are less accessible to trawling. The regional pattern of sardine distribution in recent years appears to be broadly consistent with observed local SST patterns.

The annual Canadian harvest is based on the United States assessment of coast-wide stock abundance, an assumed 10% migration rate, and the harvest rate adopted for the United States fishery. To date, 50 licensees have been allocated 300 t individual quotas, of which half were dedicated to First Nations fishers. Relatively few of these have been accessed. Further expansion of the fishery will be contingent on the development of markets and the continued northward migration and avail-

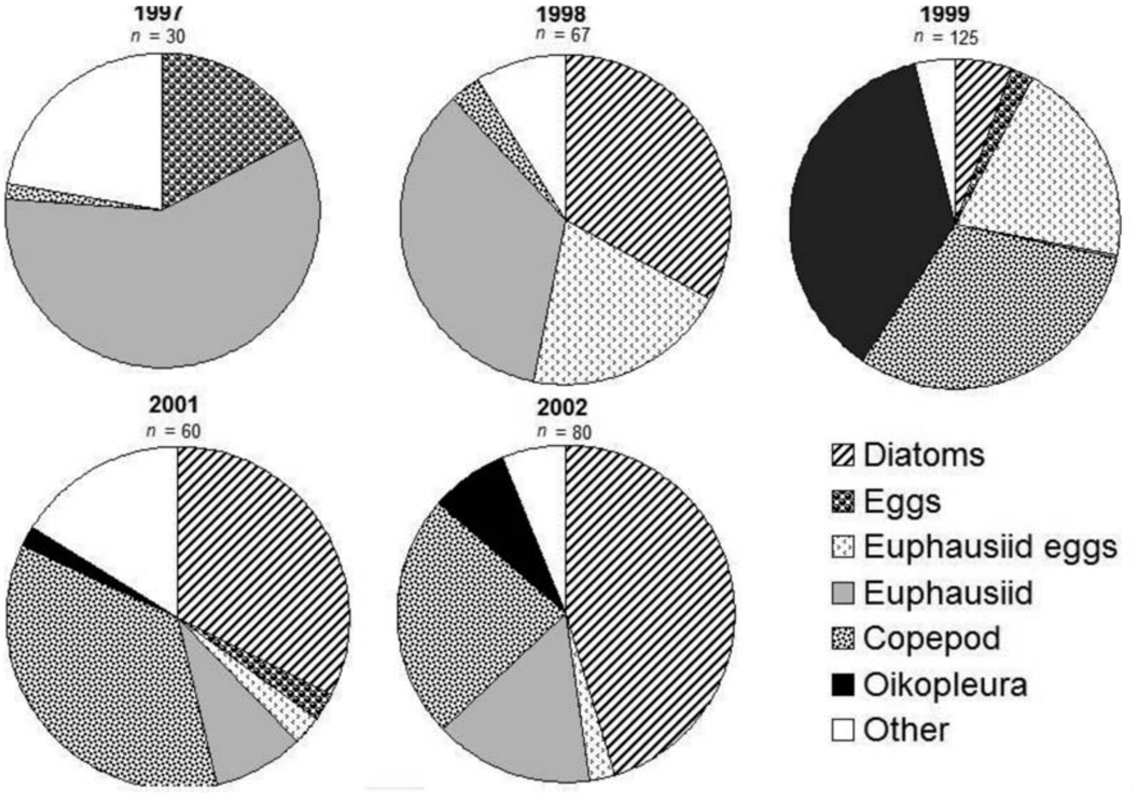

Figure 9. Major prey items by average % volume per Pacific sardine (*Sardinops sagax*) stomach, 1997–2002.

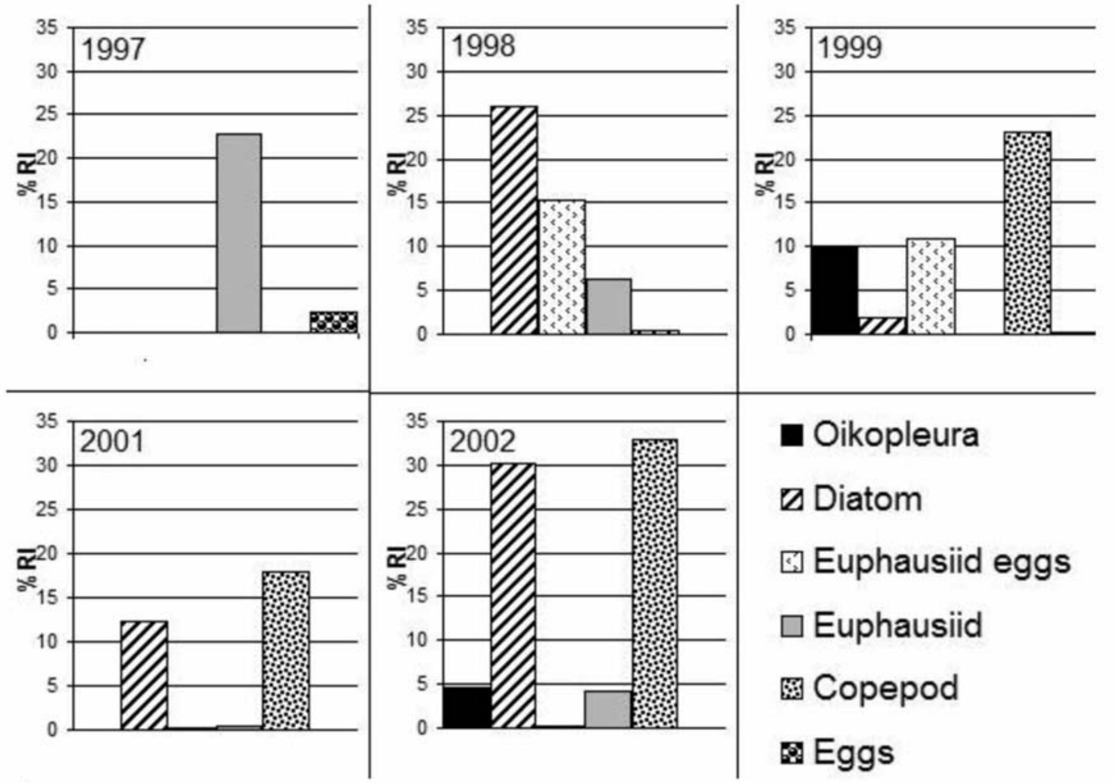

Figure 10. Major prey items of Pacific sardine (*Sardinops sagax*) by Relative Importance (%RI) value, 1997–2002.

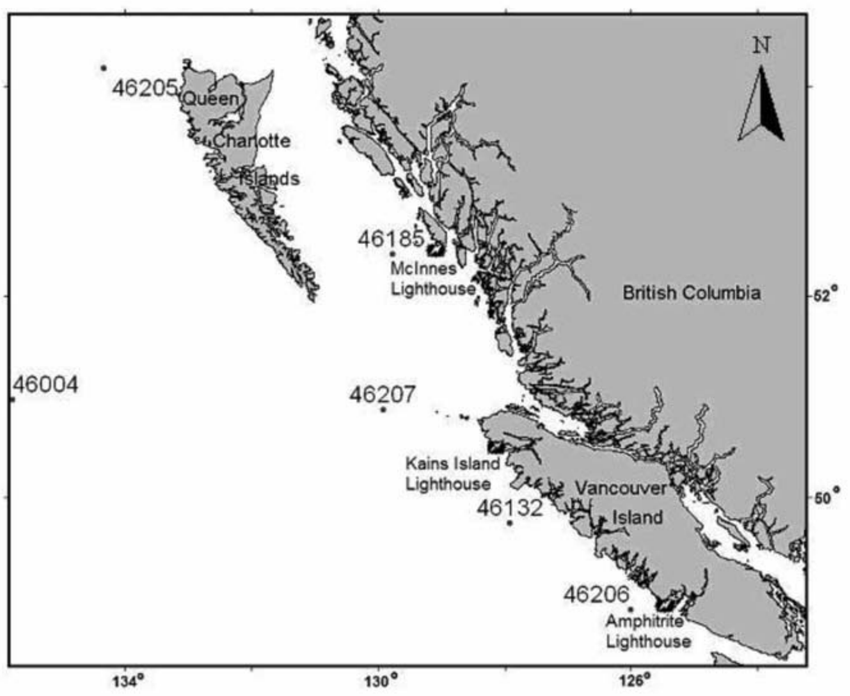

Figure 11. Location of ocean buoys (inshore and offshore) and lighthouse stations providing temperature data, 1990–2003.

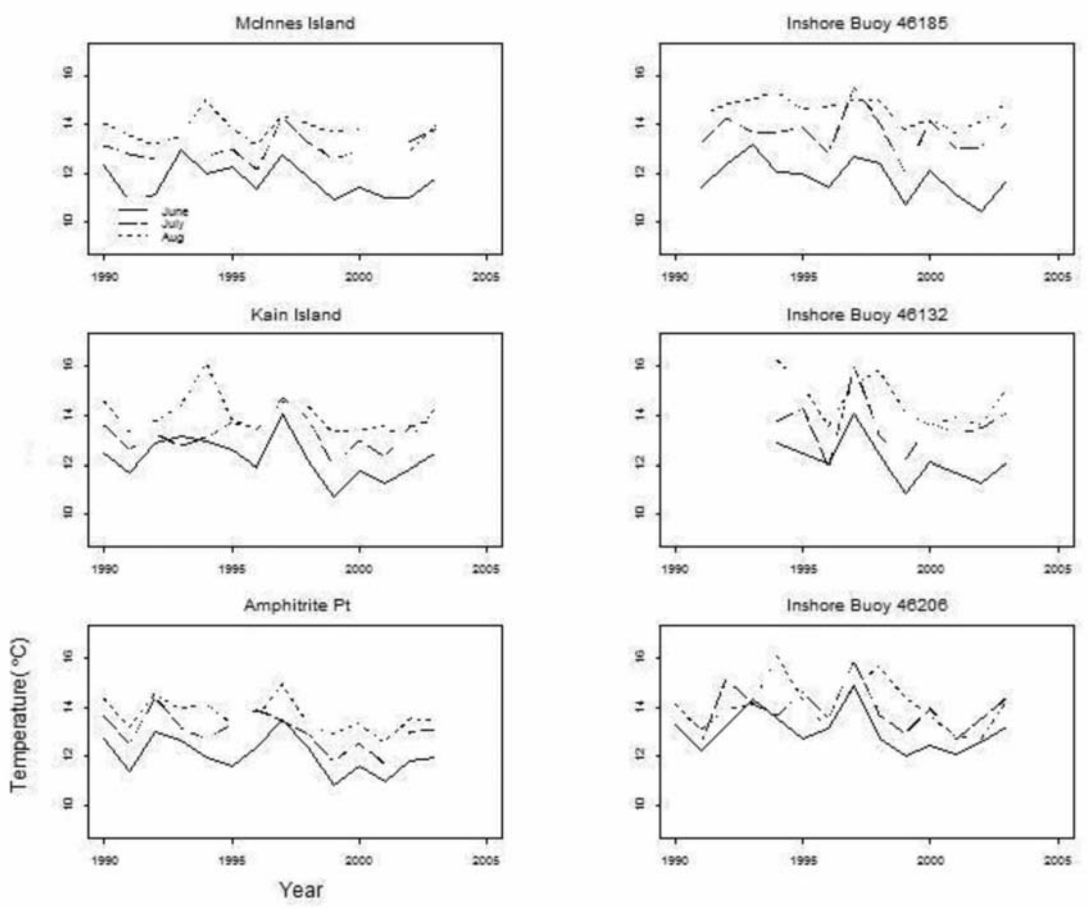

Figure 12. Sea surface temperature conditions during June–August for lighthouse stations and inshore buoys from 1990–2003 off the west coast of British Columbia.

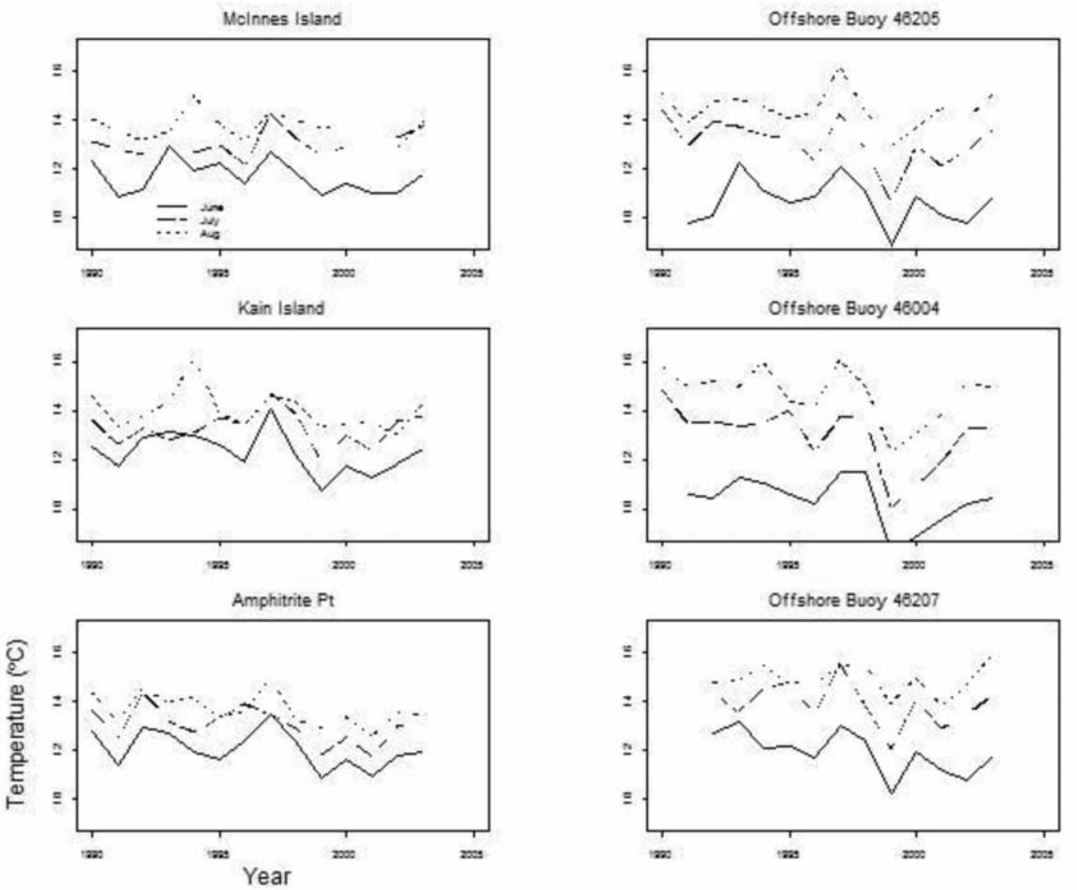

Figure 13. Sea surface temperature conditions during June–August for lighthouse stations and offshore buoys from 1990–2003 off the west coast of British Columbia.

ability of sardines in Canada. A better understanding of the biological and oceanographic factors that determine the migration timing and relative abundance or availability of sardines to Canadian fishers will be crucial to the longer-term viability of this fishery.

Historically, sardines entered British Columbia waters in mid-June and returned to southern spawning grounds (California) in mid-October. Most spawning occurred from April to June in the southern California Bight. It was primarily the older, larger sardines which migrated north to feed off British Columbia. Hart (1943) noted that in some years some sardines remained in the inlets off the WCVI throughout the winter. In 1992, sardines reappeared in British Columbia waters (Hargreaves et al. 1994) after a total absence of over 40 years. They have increased in abundance in Canadian waters and now are a dominant species in the surface waters. As in the 1930s and 1940s, it is primarily the older, larger sardines which enter Canadian waters to feed. The unexpectedly large increase in the abundance of sardines has radically changed our ideas about the causes of the collapse of sardine populations in the 1940s. The traditional explanation of overfishing being the principal cause for the collapse is no longer tenable and needs to be re-examined. It is now clear that large-scale fluctuations in oceanic conditions affected their distribution, spawning behavior, and survival. Fishing pressure undoubtedly may have affected the rate of change, but the population dynamics were reflecting the new dynamics of their ecosystem.

Dominant prey groups found in sardine diet each year match groups identified by Mackas and Tsuda (1999) as major contributors to the zooplankton biomass throughout the oceanic subarctic Pacific, both locally and at a basin scale. Mackas et al. (2001) found most zooplankton taxa underwent large year-to-year variations in abundance during the study period (1985–99) off the WCVI. For example, the euphausiids *Euphausiida pacifica* and *Thysanoessa spinifera* were low in abundance before 1987, increased in abundance in the late 1980s through the early 1990s, then levelled off or declined by the late 1990s (Mackas et al. 2001). Our diet data indicate that *E. pacifica* and *T. spinifera* were important prey items in 1998 but declined in importance thereafter. The calanoid copepod *Acartia longiremis* has been increasingly important in stomach contents since 1999 but was not identified from contents in 1998. This may also be an indication of species assemblage shifts, as Mackas et al. (2001) report a population recovery of "boreal" copepod species (*Acartia longiremis*, *Calanus marshallae*, *Pseudocalanus mimus*) in 1999 following low levels through the 1990s.

A number of biotic and abiotic factors have been examined to explain the expansion and contraction of sardine populations in the North Pacific Ocean (reviewed in McFarlane et al. 2002). Answering the question as to why sardines shifted their range northward in the early 1990s may be key to understanding the mechanism controlling their abundance changes. McFarlane and Beamish (2001) suggested that these fluctuations in abundance and northern distribution may initially be related to changes in the species composition and availability of phytoplankton in northern waters. Whatever the mechanism, it is generally recognized that the expansion and contraction of sardine populations are likely to continue in response to large-scale changes in ocean conditions. This will require assessments and management strategies that are responsive to trends in climate/ocean systems. Canadian and U.S. assessment and management strategies do not, at present, recognize these trends. However, current studies along the west coast of North America, from Canada to Mexico, are now collecting the information needed to develop future strategies which will incorporate large-scale regime changes. The information in this paper should be useful in the future development of ecosystem approaches to the management of sardines.

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SPAWNER-RECRUIT PATTERNS AND INVESTIGATION OF ALLEE EFFECT IN PACIFIC SARDINE (*SARDINOPS SAGAX*) IN THE GULF OF CALIFORNIA, MEXICO

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ABSTRACT

We analyzed stock and recruitment data of Pacific sardine (*Sardinops sagax*) from the Gulf of California, México. We used the Shepherd and Ricker stock-recruitment (*S-R*) models and included a new parameter in the *S-R* function. The new parameter, associated with the Allee effect, was defined as λ, which permitted a non-zero intercept representing recruitment failure. The general model was $R_t = (S_t - \lambda)F(S_t - \lambda,\theta)$, where R_t is recruitment, S_t is spawning stock, and θ represents the parameters in the model. Parameters were estimated using a negative log-likelihood algorithm. The λ parameter was estimated to be 287 x 10^6 spawning adults in the Shepherd model and 1,569 x 106 spawning adults in the Ricker model, with these values representing the abundance of the adult stock with zero recruitment. We proposed using λ as a reference point in the fishery. Estimates of λ did not indicate an Allee effect in the sardine population in the Gulf of California, because when the parameters in this model were estimated, we observed that estimates of recruitment were not less than the reference value of 287 million individuals. We believe the fall of abundance during 1993 and 1994 is possibly associated with environmental factors. In these years, the Pacific sardine was far from the reference point estimated by our study, and we believe that the λ parameter is a good indicator of the minimum stock size necessary to maintain the fishery.

INTRODUCTION

The Pacific sardine (*Sardinops sagax*) population in the Gulf of California has been analyzed using two hypotheses. The first explains a relationship between the environment and fluctuations in abundance (De Anda et al. 1994; Cisneros-Mata et al. 1996a; Nevárez-Martínez et al. 1999; 2001), and the second proposes a density-dependent effect (Cisneros-Mata et al. 1995; 1996b). For the first hypothesis, there is evidence that environmental variability affects Pacific sardines. Baumgartner et al. (1992) showed a reconstruction of abundance changes of Pacific sardines and anchovy (*Engraulis mordax*) from the analysis of scales deposited in anaerobic sediments. Their analysis showed changes in sardine abundance over periods of 30 years. Lluch-Belda et al. (1989; 1991; 1992a; 1992b) explained the variability in abundance as changes in distribution along the California Current according to temperature and upwelling patterns. This change in distribution is more evident when an El Niño affects the California Current (Fiedler 1984; Hayward 1993; 2000; Lea and Rosenblatt 2000). El Niño causes a shift in distribution of Pacific sardines to the northern range of the California Current. During 1992, Hargreaves et al. (1994) observed *Sardinops sagax* along the British Columbia coast, and during 1997–98 the species was observed off Alaska (Wing et al. 2000).

When these changes in distribution and abundance are measured, the population dynamics of the sardine are affected, and an Allee effect could be observed in the stock. When a school falls below its critical level, any self-regenerating abilities are lost, and school rebuilding can only occur through mixing with other schools. Frank and Brickman (2000) explained that Allee effects have been demonstrated or hypothesized for the Pacific sardine. Allee affects can arise from a general ecological process (predation) under a variety of different combinations of functional and aggregative responses. Allee effects may thus be present in a broad spectrum of different taxa with different types of life history and not only in those taxa such as broadcast spawners and cooperative breeders (Gascoigne and Lipcius 2004). An increasing number of marine species are heavily exploited or threatened with collapse; consequently, there is a need to understand the performance of populations at low population density. The vulnerability of an animal population to overexploitation depends upon its reproductive behavior and mating system (Stoner and Ray-Culp 2000). Nevárez-Martínez et al. (2001) noted that the decline (1990–93) and recovery (1994–96) of sardines were due to the environment affecting the quality and quantity of primary productivity. Although the environmental effect is an important source of variability in Pacific sardine abundance, a management strategy for Pacific sardines in the Gulf of California needs to be determined so that we can develop management goals and reference points for the fishery. In this paper, we present an analysis of stock and recruitment data to inves-

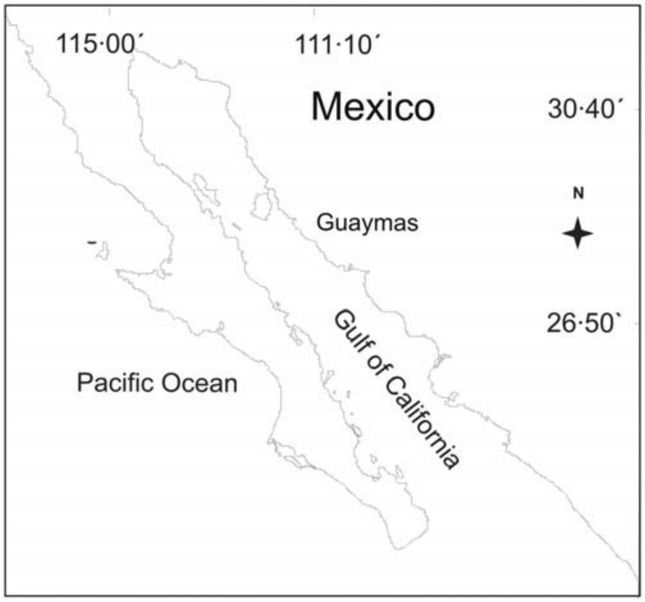

Figure 1. Study area of Pacific sardines (*Sardinops sagax*) in the Gulf of California, Mexico.

tigate the presence of an Allee effect and to identify a fishery reference point for Pacific sardines in the Gulf of California.

MATERIAL AND METHODS

Using biological and catch and effort data from the Pacific sardine fishery in the Gulf of California (fig. 1), the numbers of individuals-at-age in the sardine population were estimated using virtual population analysis (VPA) to estimate spawner and recruit abundance (Gulland 1965; Megrey 1989) from the 1971–72 through 1996–97 fishing seasons. The methods and assumptions were similar to those used by Cisneros-Mata et al. (1995) and Nevárez-Martínez et al. (1999). We used the VPA (sequential population analysis, SPA) module in FISHLAB (Darby and Flatman 1994). The number of recruits was estimated as the number of 0-age fish in each fishing season. Spawning-stock abundance was expressed as the sum of individuals from age 1 to the oldest age-group (Nevárez-Martínez et al. 1999).

Shepherd Model

We analyzed the stock-recruitment (*S-R*) relationship using a model described by Shepherd (1982) as

$$R_t = \frac{\alpha S_{t-1}}{1 + \left(S_{t-1}/\kappa\right)^{\beta}} e^{\varepsilon}, \tag{1}$$

where R_t is the recruitment size in year t, S_{t-1} is the parental stock size in the previous year, α is the maximum per capita recruitment, κ is the parental stock size above which density dependence dominates density-independent factors, and β measures the strength of density dependence (Cisneros-Mata et al. 1996b). The β parameter allows for a range of shapes in the stock-recruitment relationship. By changing β, the Shepherd model reflects (a) a dome-shaped relationship similar to a Ricker curve for $\beta = 2$ where a high abundance of spawners can reduce recruitment in future years, (b) a Beverton-Holt relationship for $\beta = 1$ where increasing the number of spawners eventually leads asymptotically to constant recruitment, or (c) a Cushing relationship for $\beta = 0.5$ where increasing spawners increases recruitment (Robb and Peterman 1998; Quinn II and Deriso 1999). The parameter ε is a normally-distributed, random-noise term with a mean = 0 and standard deviation = σ. The stock-recruitment data were analyzed in two different ways. We first excluded the period 1992–93 and 1993–94 because in those years the most important fall in Pacific sardine abundance was observed (Cisneros-Mata et al. 1995). Those authors assumed that the decline from 1989 to 1992 was an effect of overfishing, and during 1992–93 and 1993–94 the consequences were observed to be low abundance and an important fall in the landings. Additionally, during 1992 and 1993 the California Current was affected by El Niño conditions (Hayward 1993; Hayward et al. 1994), and during 1994 the California Current returned to a typical circulation pattern (Hayward et al. 1995). In our time series of *S-R* data, 1992–93 and 1993–94 showed the lowest values of spawning stock (fig. 2). In the second option, we analyzed the complete series of stock-recruitment data for 1971–72 to 1996–97 (fig. 2).

Frank and Brickman (2000) and Chen et al. (2002) proposed a natural extension of traditional *S-R* models where an Allee effect was incorporated. It is commonly known as "depensation" in fisheries (Liermann and Hilborn 2001). Despite the large number of studies supporting a depensatory mechanism, there is little evidence of depensation that is strong enough to be important in a population's dynamics (Liermann and Hilborn 1997; Myers et al. 1999; Myers 2001). However, because factors such as demographic and environmental variability make depensatory population dynamics difficult to detect, this lack of evidence should not be interpreted as evidence that depensatory dynamics are rare and unimportant (Liermann and Hilborn 2001). So the modified Shepherd model was then expressed as

$$R_t = \frac{\alpha (S_{t-1} - \lambda)}{1 + \left((S_{t-1} - \lambda)/\kappa\right)^{\beta}} e^{\varepsilon}, \tag{2}$$

where λ represents the Allee effect by permitting a non-zero intercept representing recruitment failure (Frank

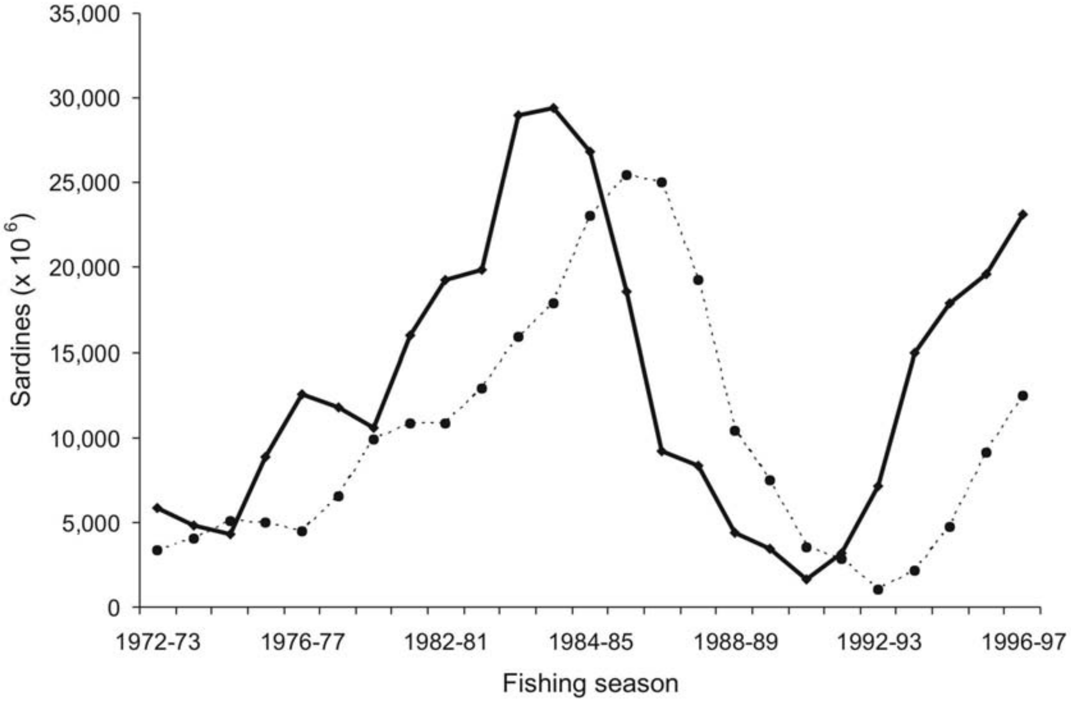

Figure 2. Time series of adult stock (dotted line) and recruitment (solid line) of the Pacific sardine (*Sardinops sagax*) in the Gulf of California, Mexico.

and Brickman 2000). Chen et al. (2002) explained that a model with depensatory-population dynamics may be used when the population is small, because then population growth declines as population density declines. A variety of processes can result in depensation at low abundance. Inbreeding may occur, spawning fish may not find mates, higher mortality may result from predator saturation or fishing, and poor conditioning of the spawning environment and low efficiency of food location may result. The evidence for a depensatory mechanism may be grouped according to four categories: (a) reduced probability of fertilization, (b) impaired group dynamics, (c) conditioning of the environment, and (d) predator saturation (Liermann and Hilborn 2001). When abundances are low, depensation will accelerate population declines and increase the probability of collapse. If we include depensatory effects, stock rebuilding could be delayed or prevented (Chen et al. 2002). In Pacific sardines, the decline observed in landings during 1992–93 and 1993–94 could have been a risk of collapse in this fishery. Cisneros-Mata et al. (1996b) noted that the intrusion of anomalous warm-water masses shortens the spawning season and forces adult distribution northward, and this mechanism probably increases cannibalism in the Pacific sardine in the Gulf of California.

The θ parameters in the modified Shepherd model (equation 2) were estimated using a negative log-likelihood estimator:

$$-\log L(\theta / data) = \sum_{t} \left[-\frac{1}{2} * \ln(2 * \pi) \right] - \left[\frac{1}{2} * \ln(\sigma^2) - \frac{(\ln R_O - 1\mathrm{n} R_E)^2}{2 * \sigma^2} \right], \qquad (3)$$

where t is brood year, and the θ parameters were α, β, κ, and λ. In this case, θ indicates the combination of hypothesized parameter values for the Shepherd model, R_O is the observed recruitment, and R_E is the estimated recruitment. For σ the analytical solution was proposed as

$$\sigma = \sqrt{\frac{1}{n} \sum_{t=1}^{n} (1\mathrm{n}R_O - 1\mathrm{n}R_E)^2}\ , \qquad (4)$$

where n is the number of years in the S-R data series (Hilborn and Walters 1992).

Confidence Intervals

To estimate the confidence intervals for the parameters in the modified Shepherd model, we used the likelihood profile (Venzon and Moolgavkor 1988; Hilborn and Mangel 1997) because it can be used to determine confidence intervals for the θ parameters either jointly or individually. The confidence intervals for the parameters were estimated based on the χ^2 distribution with m degrees of freedom (Zar 1974). For a single parameter p, the confidence interval was defined as all values of p that satisfy the inequality

$$2[L(Y|\ p_{est}) - L(Y|\ p)] < \chi^2_{1,1-\alpha}, \qquad (5)$$

where $L(Y|\ p_{est})$ is the negative log-likelihood of the most likely value of p, and $\chi^2_{1,1-\alpha}$ gives the values of the χ^2 distribution with 1 degree of freedom at a confidence level of $1-\alpha$. Thus, the 95% confidence interval for p encompasses all values of p that are twice the difference between the negative log-likelihood and the negative log-likelihood of the best estimate of p, which is less than 3.84 (Pawitan 2001).

Ricker Model

We also analyzed the data using a Ricker model $R_t = \alpha S_{t-1} e^{-\beta S_{t-1}} e^{\omega_t}$, where α is the parameter associated with density-independent mortality, β is the parameter associated with density-dependent mortality, and ω is the error normally distributed with a mean = 0 and a standard deviation = σ. Parameter values in the Ricker model were computed according to the negative log-likelihood estimator described in equation (3).

Where θ parameters were α and β, θ indicates the combination of hypothesized parameter values for the Ricker model. The standard deviation was computed with equation (4), and ω_t was estimated as

$$\omega_t = 1\mathrm{n}\left(\frac{R_t}{\alpha S_{t-1}}\right) + (\beta S_{t-1}). \qquad (6)$$

When the λ parameter was incorporated into the Ricker equation, the *S-R* relationship was expressed as $R_t = \alpha(S_{t-1} - \lambda)e^{-\beta(S_{t-1}-\lambda)}e^{\omega_t}$. This equation was defined as the modified Ricker model (Chen et al. 2002). The parameters' values were estimated according to the negative log-likelihood estimator shown in equation (3), and the θ parameters were α, β, and λ.

For the Ricker model and the modified Ricker model, the parameters were estimated with a nonlinear fit using the Newton algorithm (Neter et al. 1996). Confidence intervals for parameters in these equations were computed from the likelihood profiles described in equation (5). Estimations of likelihood were computed as $L_i = \exp^{-\log L_i}$, where L denotes likelihood, and i means the modified Shepherd model, Ricker model, or modified Ricker model.

Akaike's Information Criterion

We compared the different model fits using Akaike's information criterion (AIC) $AIC = (2 \times -\log L) + (2 \times \theta)$, where $-\log L$ was the negative log-likelihood estimated in equation (5), and θ represents the number of parameters in each model. The smallest AIC is for the best model (Haddon 2001).

RESULTS

The parameters for the Shepherd and Ricker models are shown in Table 1, and the confidence intervals ($P < 0.05$) are shown in Table 2. The modified Shepherd model showed an estimation of the λ parameter lower than that estimated by the modified Ricker model. The non-zero intercept representing recruitment failure in the Shepherd model was 287 million spawners, whereas that of the Ricker model was 1,569 million spawners. The α and β parameters were similar in the modified and typical Ricker models. However, the modified Ricker model shows likelihood higher than that of the Ricker model (tab. 1). Likelihoods computed for the modified Shepherd model and modified Ricker model were similar. The observed value of recruitment fitted to the modified Shepherd model is shown in Figure 3. Estimates of spawners derived from virtual population analysis were not less than the reference value of 287 million individuals.

Estimations of the likelihood profiles and their confidence intervals ($\chi^2_{1,1-\alpha}$) for the modified Shepherd model are shown in Figures 3–6. The λ parameter (fig. 4) shows a likelihood profile with negative values. The trend

TABLE 1
Parameters and Likelihood Estimated for the Different Stock-recruitment Models. λ is Expressed in Millions of Individuals

	λ	α	κ	β	Likelihood
1) Modified Shepherd Model	287	1.4	23,339	5.43	1.87E-09
2) Ricker Model		2.3		5.1E-5	5.13E-12
3) Modified Ricker Model	1,569	2.55		5.4E-5	1.58E-09

TABLE 2
Confidence Intervals Estimated from Negative Log Likelihood Profiles ($P < 0.05$) for Parameters of the Different Stock-recruitment Models

	λ	α	κ	β
1) Modified Shepherd Model	–500 – 900	1.2 – 1.6	21,000 – 33,000	2.5 – 11.0
2) Ricker Model		1.8 – 2.8		3.0E-5 – 7.2E-5
3) Modified Ricker Model	240 – 2,280	2.0 – 3.2		3.4E-5 – 7.4E-5

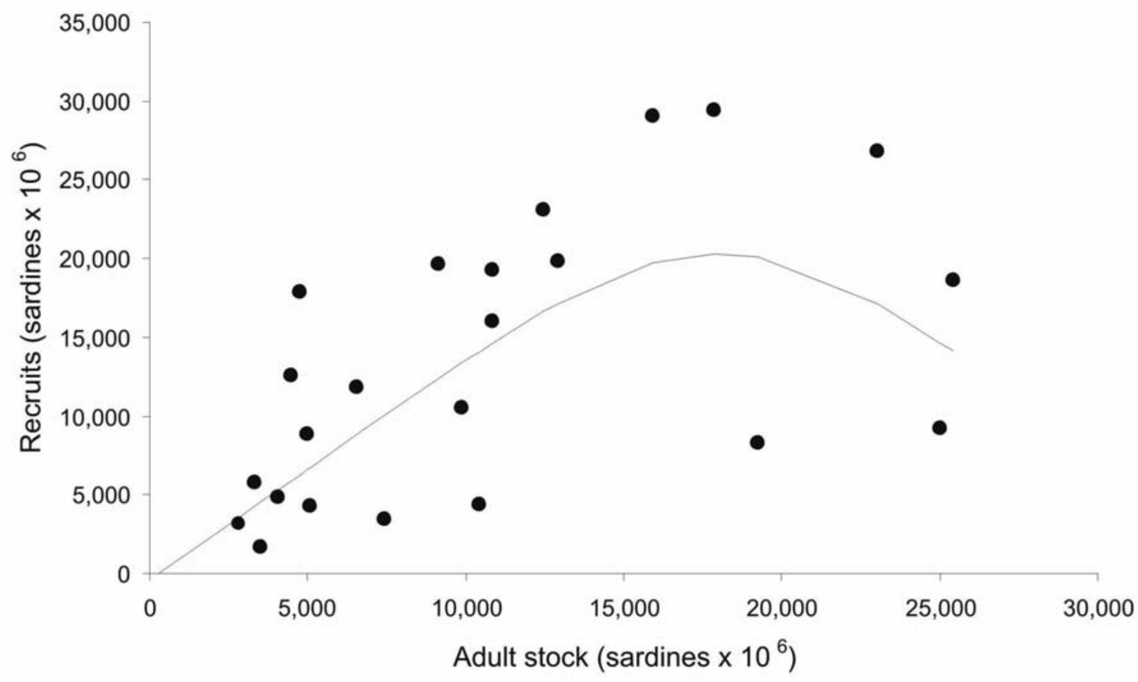

Figure 3. Recruitment of Pacific sardine (*Sardinops sagax*) estimated by the modified Shepherd model.

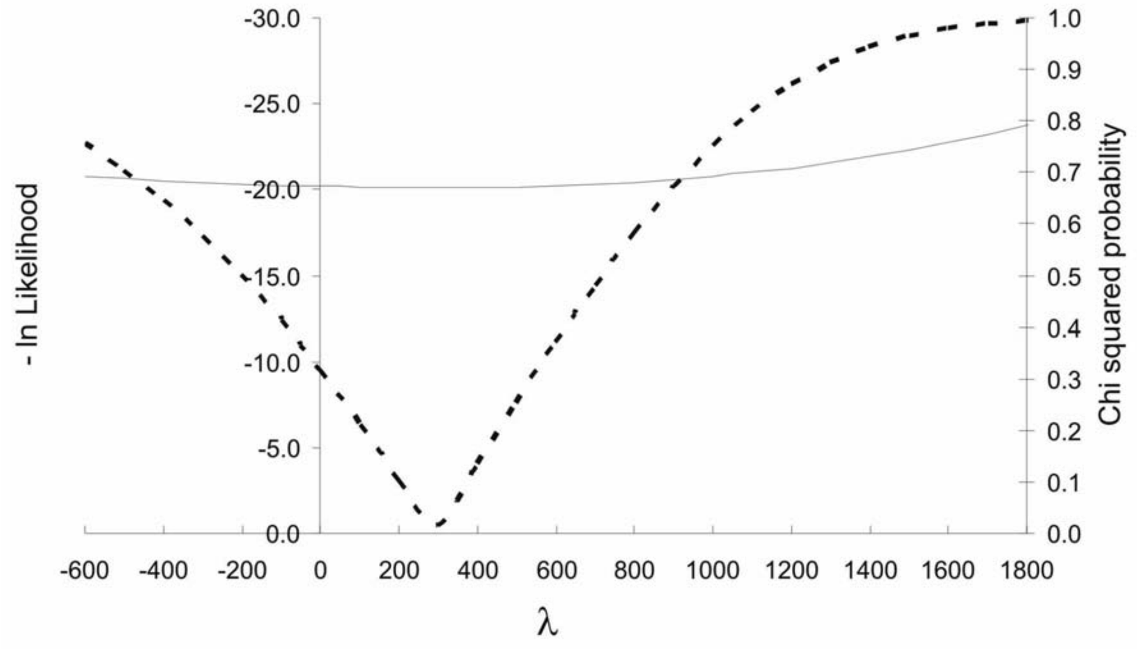

Figure 4. Likelihood profile of the lambda parameter of the modified Shepherd model. The solid line is the likelihood profile, and the dotted line is χ^2 probability.

of this parameter is not defined because the maximum likelihood is a flat line, and there are negative values for λ, and it does not explain the recruitment failures of the Pacific sardine from the Gulf of California. The α parameter shows a well-defined likelihood profile, and its confidence intervals were accurate (fig. 5). The κ and β parameters showed the same trend as λ, however it was possible to estimate confidence intervals for both parameters without computing negative values (fig. 6 and 7). The κ parameter was more accurate than β, and the likelihood profile of κ was similar to α.

The observed values of recruitment fitted for the Ricker model are shown in Figure 8. The likelihood profiles for parameters α (fig. 9) and β (fig. 10) showed that the α parameter had a better estimation of confidence intervals than the β parameter. Apparently, the

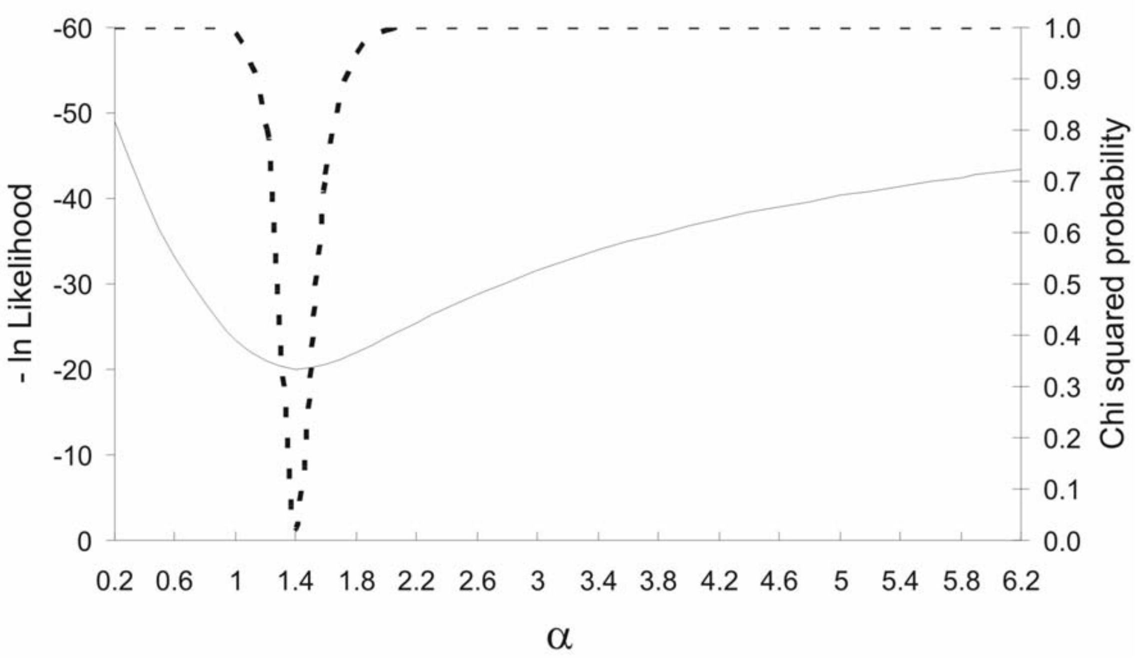

Figure 5. Likelihood profile of the alpha parameter of the modified Shepherd model. The solid line is the likelihood profile, and the dotted line is χ^2 probability.

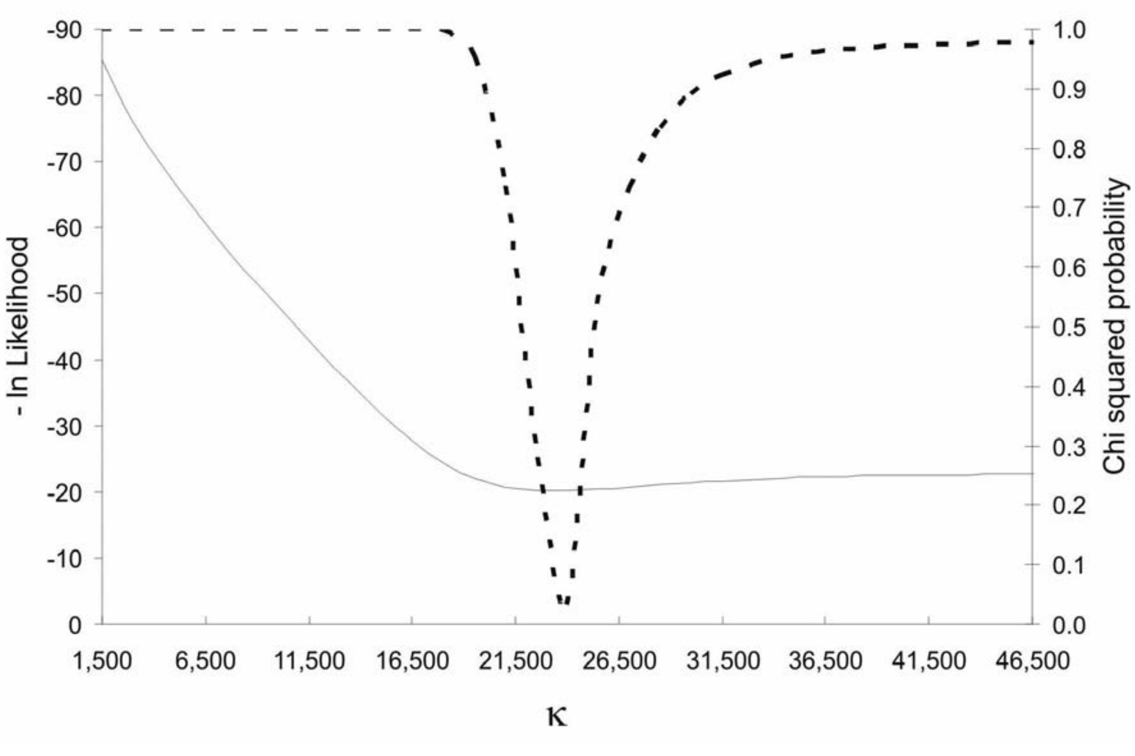

Figure 6. Likelihood profile of the kappa parameter of the modified Shepherd model. The solid line is the likelihood profile, and the dotted line is χ^2 probability.

likelihood profile of β is flat compared to α. When we compared the fits obtained with the Ricker model and modified Ricker model (fig. 11), the non-zero intercept (λ) (fig. 12) was estimated at 1,569 million spawners. This was five times greater than λ for the modified Shepherd model (tab. 1). The estimates of the number of spawners from the sequential population analysis were not lower than the value of the non-zero intercept,

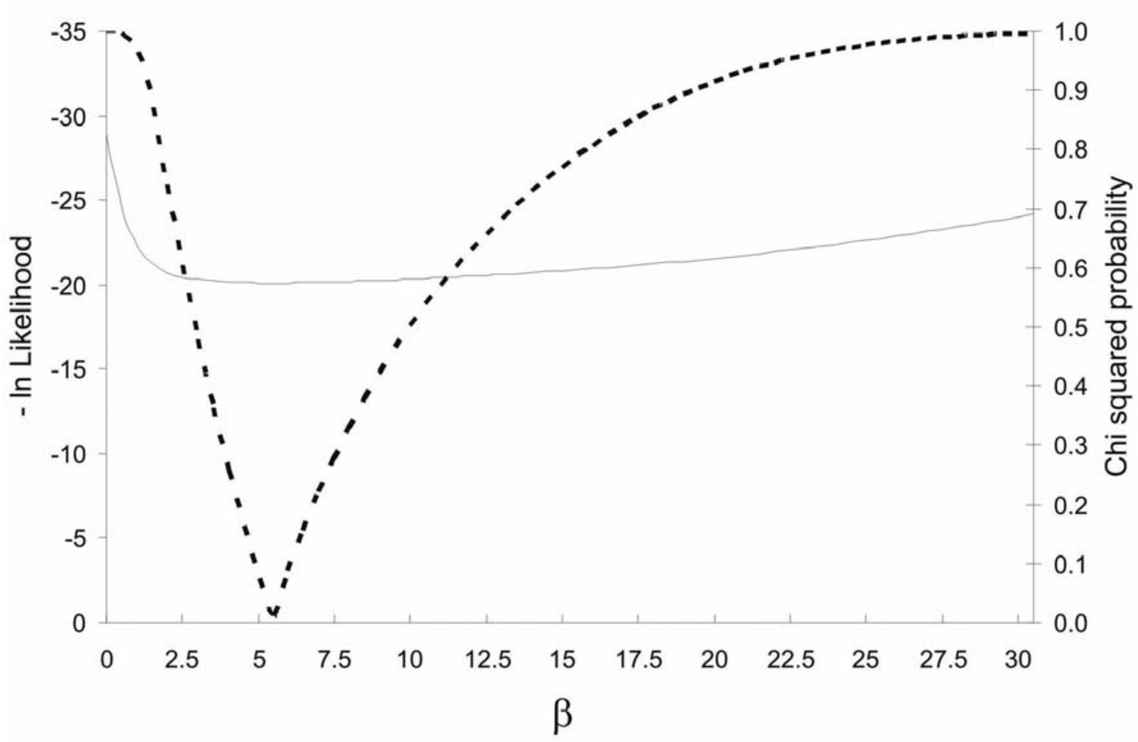

Figure 7. Likelihood profile of the beta parameter of the modified Shepherd model. The solid line is the likelihood profile, and the dotted line is χ^2 probability.

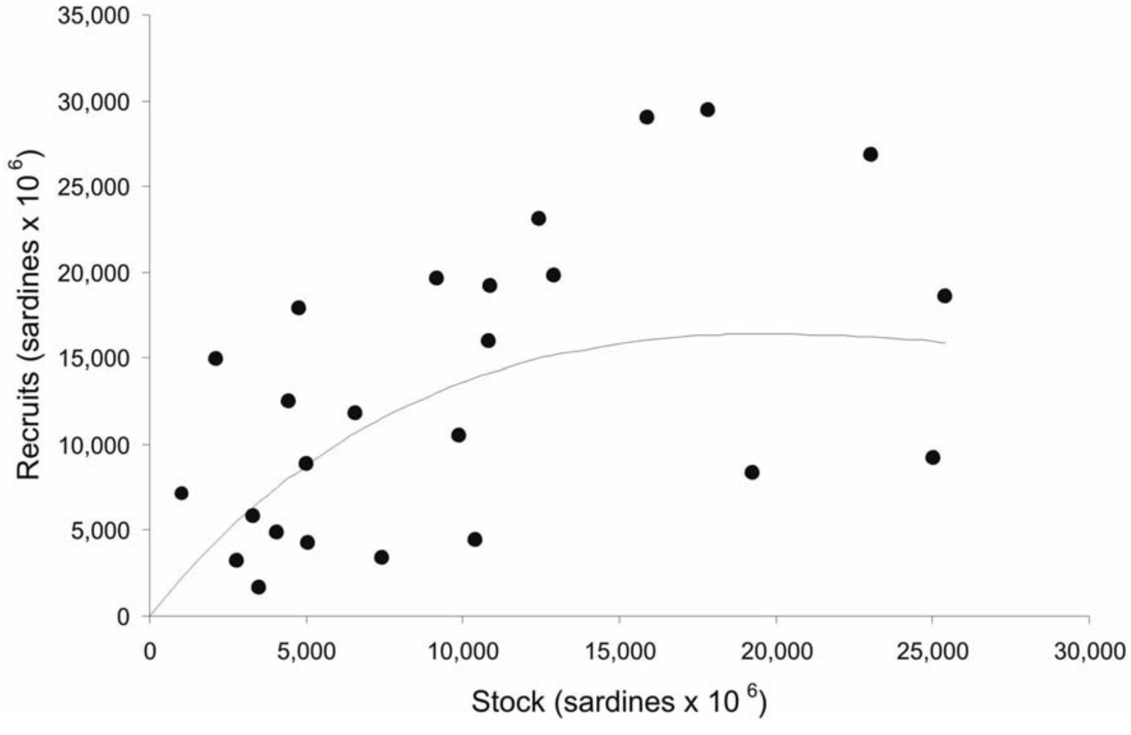

Figure 8. Recruitment of Pacific sardine (*Sardinops sagax*) estimated for a Ricker model.

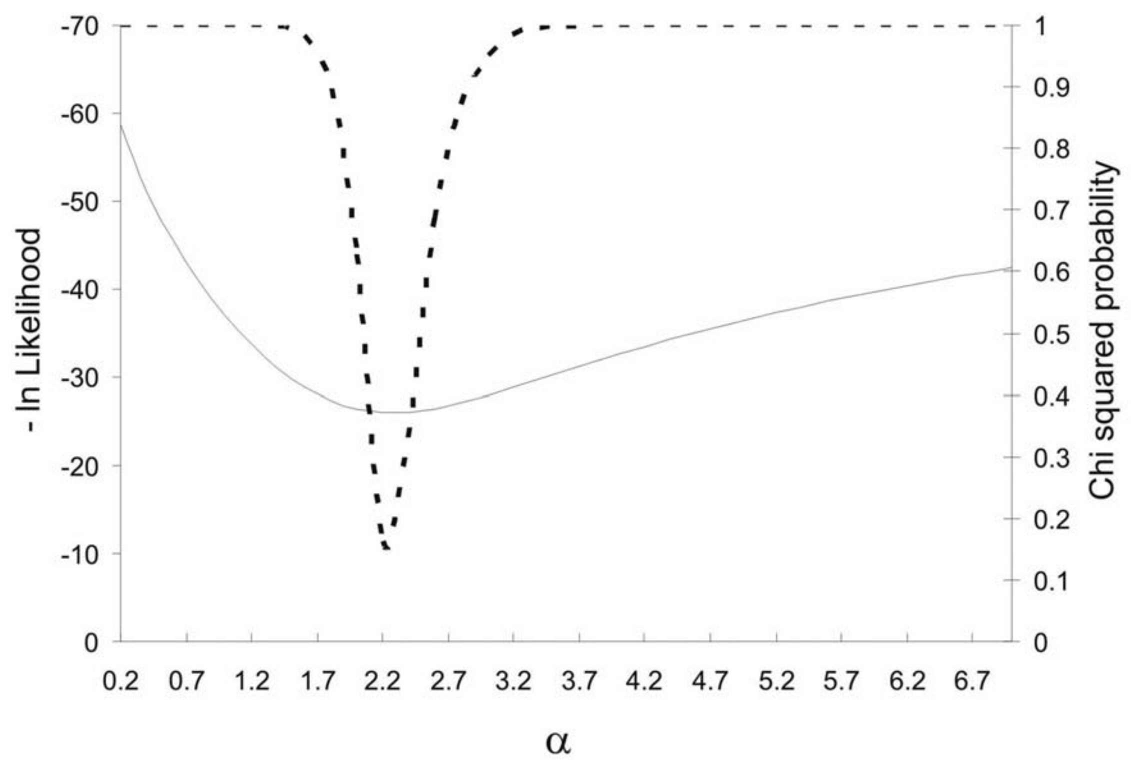

Figure 9. Likelihood profile of the alpha parameter of a Ricker model. The solid line is the likelihood profile, and the dotted line is χ^2 probability.

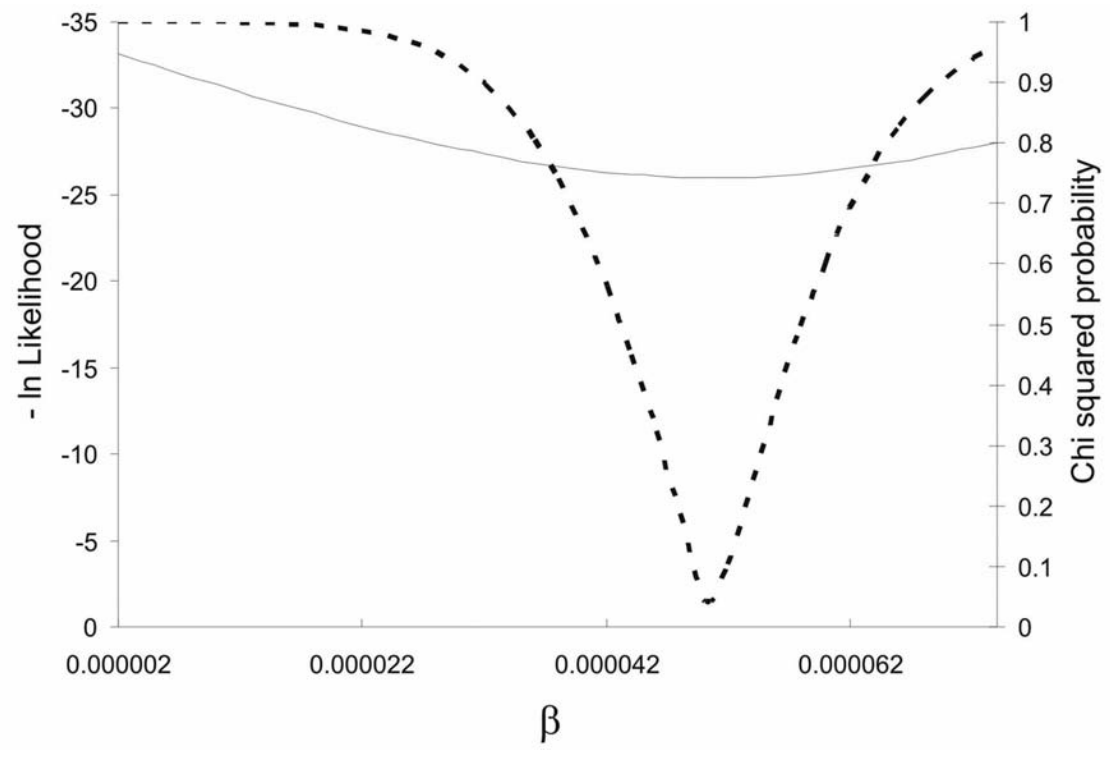

Figure 10. Likelihood profile of a beta parameter of a Ricker model. The solid line is the likelihood profile, and the dotted line is χ^2 probability.

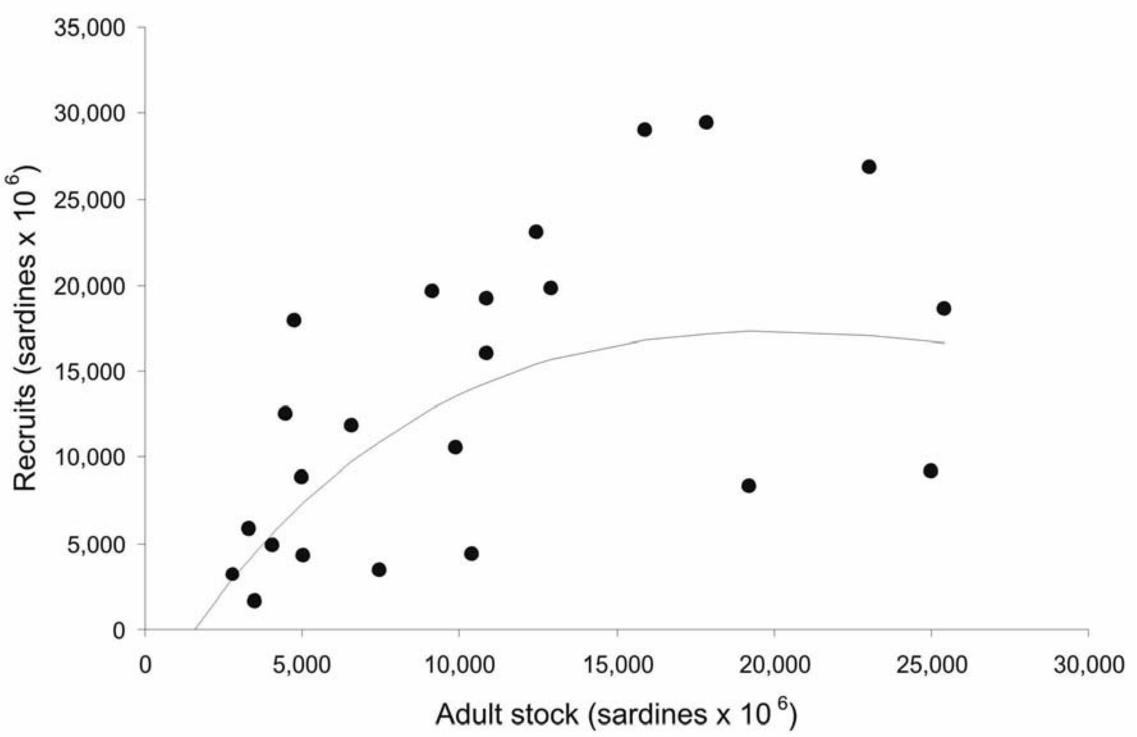

Figure 11. Recruitment of Pacific sardine (*Sardinops sagax*) estimated for a modified Ricker model.

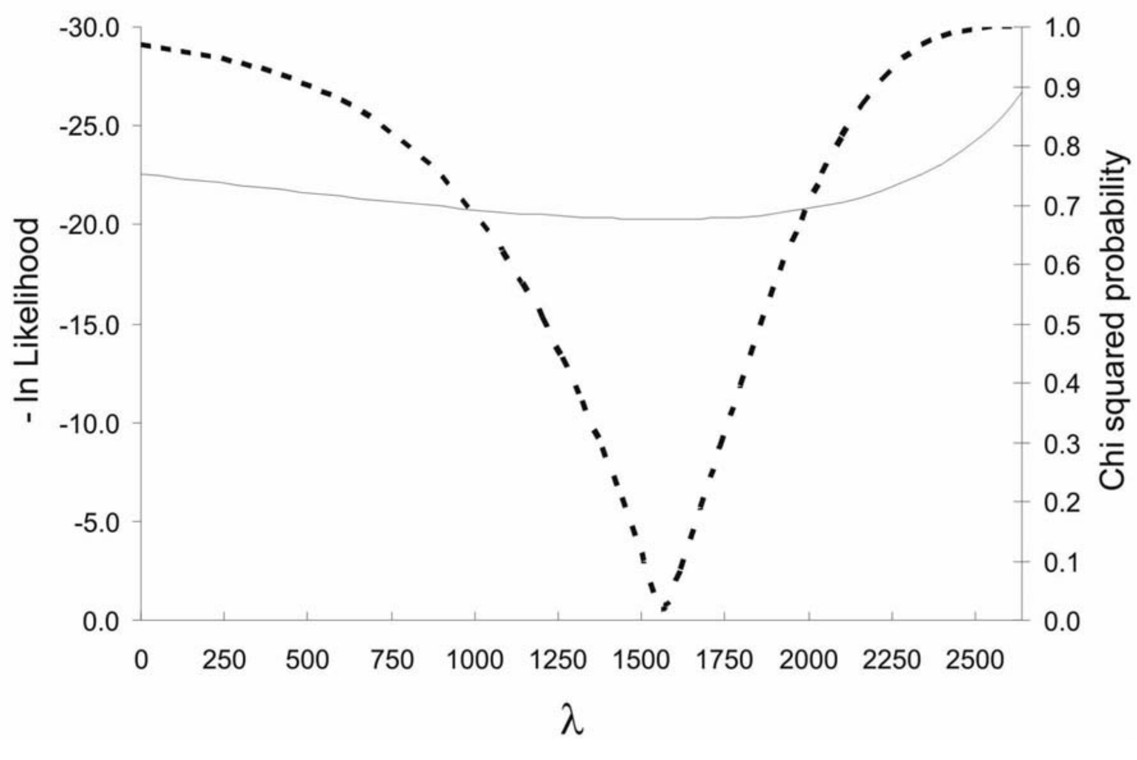

Figure 12. Likelihood profile of the lambda parameter of a modified Ricker model. The solid line is the likelihood profile, and the dotted line is χ^2 probability.

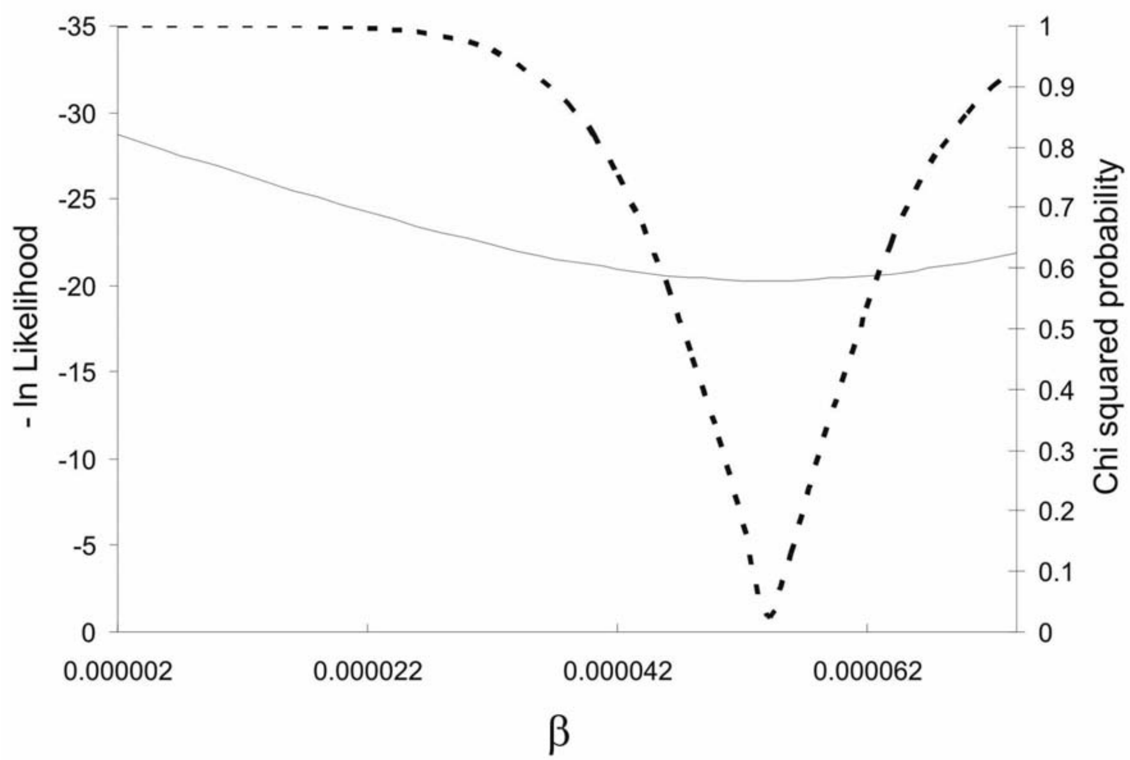

Figure 13. Likelihood profile of the beta parameter of a modified Ricker model. The solid line is the likelihood profile, and the dotted line is χ^2 probability.

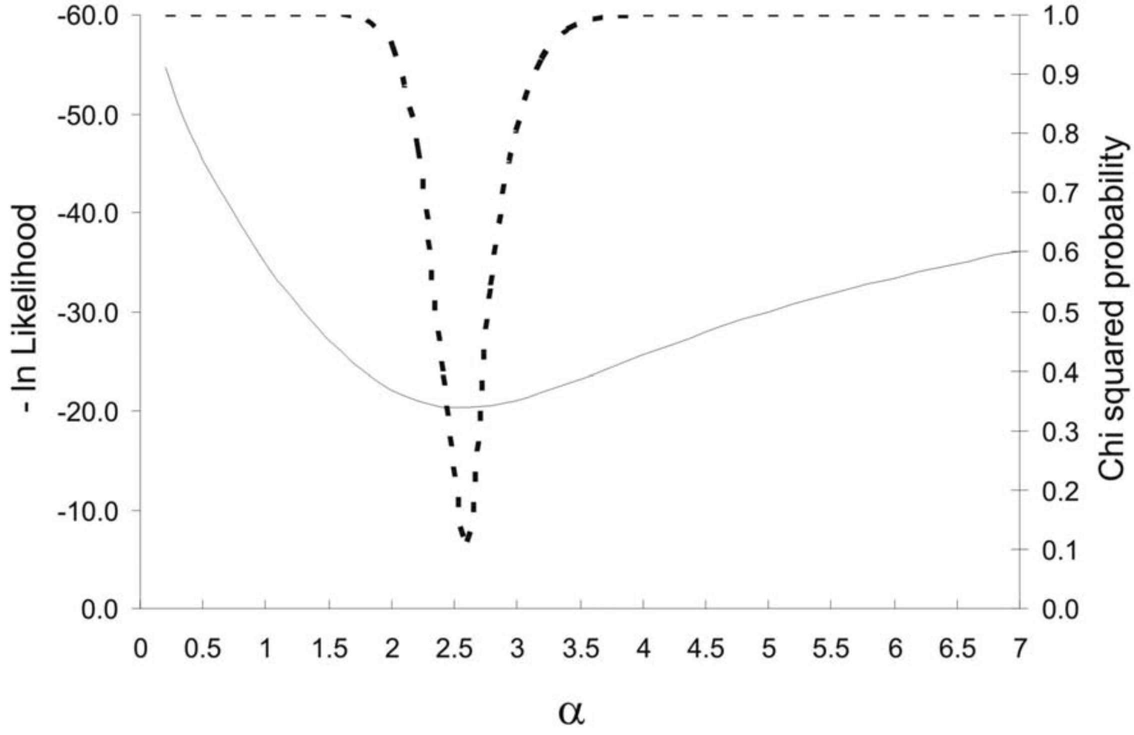

Figure 14. Likelihood profile of the alpha parameter of a modified Ricker model. The solid line is the likelihood profile, and the dotted line is χ^2 probability.

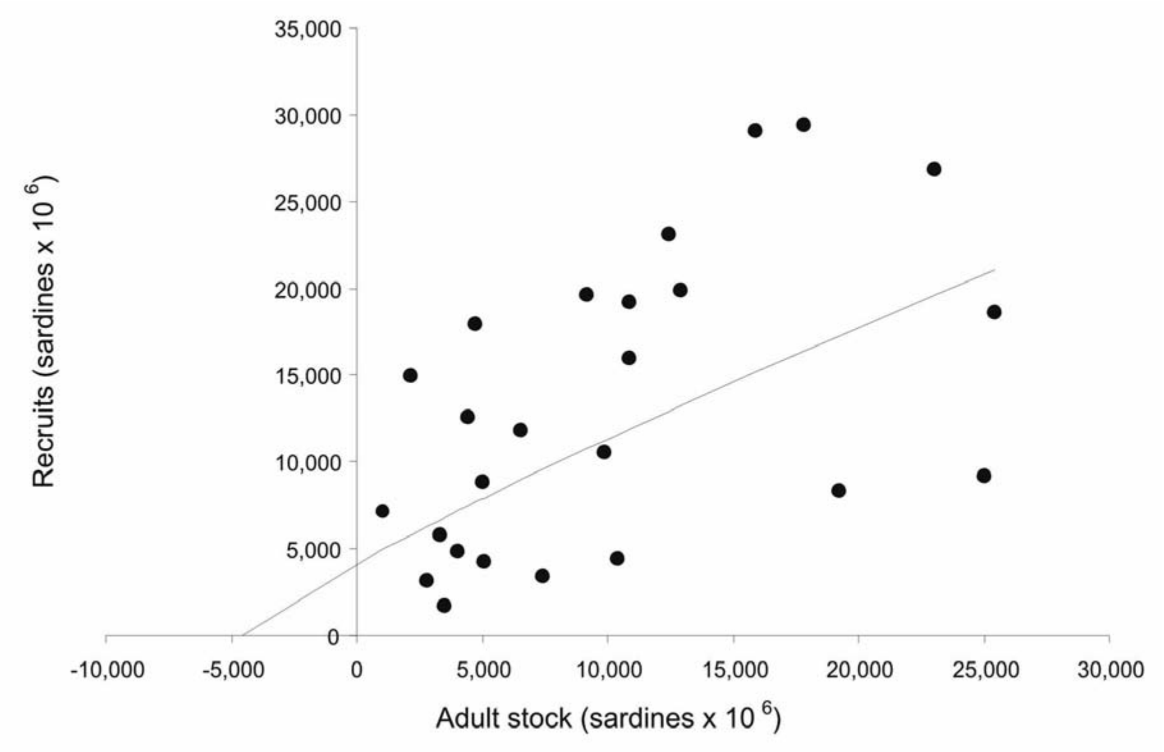

Figure 15. Stock-recruitment relationship of the Pacific sardine (*Sardinops sagax*) with a modified Shepherd model. This estimation includes complete time series of S-R data, from 1971 to 1997.

whereas β (fig. 13) and α (fig. 14) showed a trend similar to that of the Ricker model.

When the complete time series of *S-R* data were analyzed from 1971 to 1997, including 1993 and 1994, the estimates of λ in the modified Shepherd model were negative (fig. 15). The model showed an *S-R* relationship in which it was not possible to establish a reference point because the minimum stock size was negative, $\lambda = -4{,}558$, and the other parameters were $\alpha = 3.38$, $\kappa = 17.2$, and $\beta = 0.17$. This negative estimate of λ was observed as a consequence of variability in the stock and recruitment data.

Table 3 shows the results calculated for Akaike's information criterion. AIC values indicate that the best model was the modified Ricker model (46.52), for which the AIC was slightly less than for the modified Shepherd model (48.19). The AIC values of these models that included the λ parameter were better than that of the Ricker model (55.99). This result suggests that the inclusion of the λ parameter did not affect the performance of the model to fit stock-recruitment data. Although estimated AIC values for the modified Ricker model and modified Shepherd model were close, the main difference was the λ estimate, because the modified Ricker model computed 1,569 million spawners and the modified Shepherd model estimated 287 million spawners. This analysis shows there is no evidence of an Allee effect in the Pacific sardine in the Gulf of California. The number of spawners estimated with λ represents the reference point computed for stock recruitment data from the Gulf of California, and in our time-series of spawners they are greater than λ.

TABLE 3
Selection of the Best Model Based in AIC

	–log Likelihood	Number of Parameters	AIC
1) Modified Shepherd Model	–20.09	4	48.19
2) Ricker Model	–25.99	2	55.99
3) Modified Ricker Model	–20.26	3	46.52

DISCUSSION

The Pacific sardine population is characterized by high variability in abundance which affects the availability, distribution, production, and uncertainty in the fishery. It is important to maintain strong recruitment for the sardine fishery. Lasker (1985) mentioned that the solution to the stock-recruitment problem is to determine the minimum population for a species that ensures its recovery. However, it was also later noted that there was no definable minimum stock size for each species and stock, and this minimum stock size is necessary to understand the population dynamics (Watanabe et al. 1995). In this way, a reference point for populations under fishing pressure needs to be established. The reference point is defined as a conventional value derived from technical analysis, which represents a state of the fishery or population, and whose characteristics are believed to be useful for the management of the unit stock (Caddy and Mahon 1995).

In our results, we observed that the modified Shepherd model and modified Ricker model demonstrated good performance in estimating λ values. In both cases, λ represents a reference point for the stock-recruitment relationship. In the modified Shepherd model it was 287 million spawners, and in the modified Ricker model it was 1,569 million. Depensation could be observed if the sardine fishery exhibits low abundance (Liermann and Hilborn 2001). The changes in abundance of Pacific sardines in the Gulf of California were explained by Rodríguez-Sánchez et al. (2002) who illustrated that the population of *Sardinops sagax* changes its location within the ocean habitat. They suggested that the rise of a new sardine fishery inside the Gulf of California in the 1970s was the result of this population movement. Another example of this was illustrated by Hargreaves et al. (1994) and Wing et al. (2000) who found sardines in British Columbia and the Gulf of Alaska. We assume that during 1993–94 there were several factors (environment, population movement, and low spawning activity) that determined this particular shift in the population and catch (Nevárez-Martínez et al. 2001). This is because the California Current was affected by an El Niño in 1992 and 1993 (Hayward 1993; Hayward et al. 1994), and during 1994 the California Current returned to a typical circulation pattern (Hayward et al. 1995). The model performed poorly in estimating parameters when 1993 and 1994 were included in the complete time series of the *S-R*. The main effect was on the measurement of λ (fig. 15). Because 1993–94 is particularly anomalous, the approximation excluding this period could be an excellent approach for the Pacific sardine fishery. This reference point provides the primary mechanism by which the precautionary approach can be used. Our results did not show evidence of depensation in the Pacific sardines in the Gulf of California.

The λ value estimated with the modified Shepherd model is near the origin (see fig. 3), so the model implies that depensation is not present in the Pacific sardine. However, the modified Ricker model is far from the origin (see fig. 11), and there are points of stock-recruitment close to the λ value. Apparently, the modified Ricker model could indicate that the fishery needs an analysis of its management strategy to avoid depensation. Cisneros-Mata et al. (1995) believed that overfishing had an important role in the population decline of sardines in the Gulf of California from 1989 to 1992. The main risk to this sardine population is recruitment overfishing. This is understood to occur when spawning biomass is so low that recruitment decreases substantially and perhaps precipitously. In the context of our analysis, we define recruitment overfishing as a level of fishing pressure that reduces the spawning biomass produced by a year-class over its lifetime below the spawning biomass of its parents, on average (Sissenwine and Shepherd 1987). Our analysis is not focused to identify recruitment overfishing, because detecting it is complicated in most stocks by extreme recruitment variation due to factors other than spawning-stock size and by the unrepresentative sampling of *S-R* observations that occur when environmental effects are allowed to influence stock sizes over time (Walters 1990). Nevárez-Martínez et al. (2001) illustrated this when they analyzed survey research data and found a period of low relative abundance from 1990 to 1993 and one of high abundance between 1993 and 1996. In this study, the environment correlated successfully with upwelling and the sea surface temperature. As a consequence, the difference in λ estimates may be hidden because the resource-environment interaction was not measured in the modified Shepherd model (fig. 4) and modified Ricker model (fig. 12). The environment may be responsible for the "school trap" and possibly for the Allee effect for small pelagics. "School trap" was explained by Cury et al. (2000). They provided an empirical demonstration of the tendency for members of two or more pelagic schooling species of similar size and body shape to form mixed schools when abundance of one of the interacting species was low. The unfortunate outcome of this arrangement may be that the less abundant species would effectively be entrained into the life-history behavior of the more abundant species. This would put the less abundant species at risk with a critical disadvantage in growth, survival, and spawning success. We observed that λ for the modified Shepherd model estimated a confidence interval with negative values; evidently there is uncertainty in the parameter. We think that the critical-level stock must be higher, so we agree with the AIC; the Pacific sardine fishery was possibly far from the depensation effect during 1993–94.

An analysis is required to establish the reference point in the Pacific sardine, and we must evaluate the probability of the consequences of various management actions using the λ parameter as a reference point. That approach allows us to examine a stock complex consisting of numerous schools. This will show a stock-recruitment relationship that does not intercept the origin, but rather exhibits zero recruitment at some minimum stock size (Frank and Brickman 2000). We are interested in illustrating that the Pacific sardine in the Gulf of California has a minimum adult stock size. It is possible that when this adult stock is at low densities there is low egg fertilization (Allee effect). Cisneros-Mata et al. (1996b) commented that the existence of density-dependence in small pelagic fish has been questioned, probably because of the difficulty of finding convincingly supportive empirical data. Recruitment success in these species has been related to environmental indicators, such as plankton biomass or the annual sea temperature. A probable mechanism that results in increased cannibalism in the Gulf of California is the intrusion of anomalous warm-water masses that shorten the spawning season and force adult distribution northward (Cisneros-Mata et al. 1996a). Jacobson et al. (2001) analyzed eight anchovy and nine sardine stocks around the world. They showed that environmental effects are likely to contribute more variance to the annual surplus production and the instantaneous surplus production-rate than density-dependent effects for anchovy and sardine stock. This environment effect was also found by Morales-Bojórquez et al. (2003) who analyzed the stock-recruitment relationship to Pacific sardines along the southwest coast of the Baja California peninsula, Mexico and identified changes in the density-independent mortality associated with the sea surface temperature when it was >19.3°C.

The fall in Pacific sardine abundance may be explained from a process that is density-independent for environmental effects. Watanabe et al. (1995) suggested two explanations for a recruitment failure. One is low egg production from a reduced spawning biomass, or low spawning activity of adult fish, and the other is high mortality in the early life stages before recruitment to a fishing stock. Nevárez-Martínez et al. (2001) commented that the decline (1990–93) and recovery (1994–96) of sardines were due to the environment affecting the quality and quantity of primary productivity. In conclusion, we did not observe an Allee effect in the sardine population in the Gulf of California. The fall of abundance during 1993 and 1994 is possibly associated with environmental factors (Nevárez-Martínez et al. 1999; 2001). In those years, the Pacific sardine was far from the reference point estimated with our study, and we believe that the λ parameter is a good indicator of the minimum stock size necessary to maintain the fishery.

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